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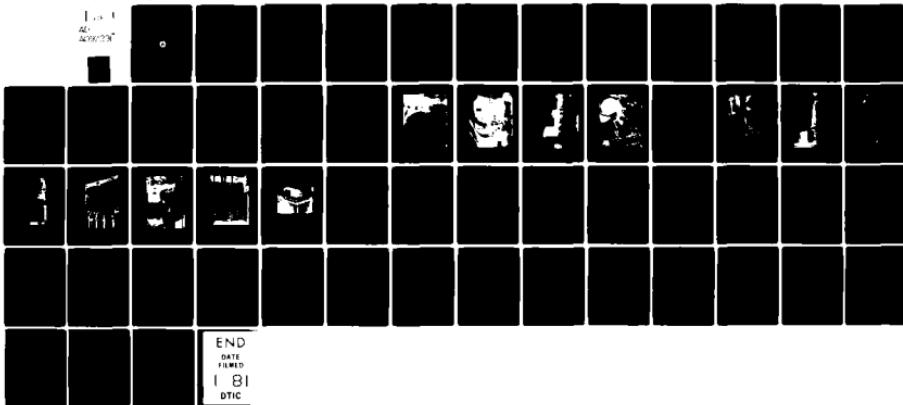
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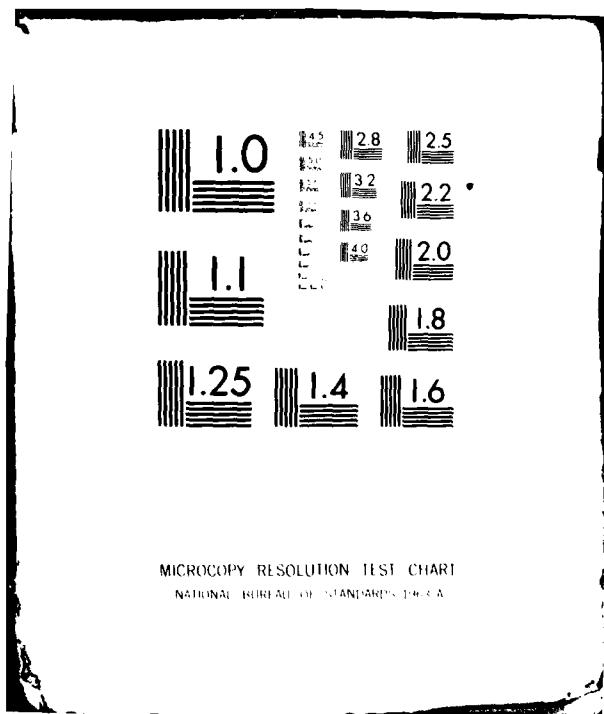
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**EXHAUST EMISSION CHARACTERISTICS AND VARIABILITY
FOR MAINTAINED GENERAL ELECTRIC CF6-50 TURBOFAN ENGINES**

AD A092291

Gary Frings

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FINAL REPORT

SEPTEMBER 1980

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the National Technical Information Service,
Springfield, Virginia 22161.

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Prepared for

**U. S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
TECHNICAL CENTER**
Atlantic City Airport, New Jersey 08405

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Technical Report Documentation Page

1. Report No. 14 FAA-CT-80-36	2. Government Accession No. AD-A092 297	3. Recipient's Catalog No. 11	
4. Title and Subtitle G EXHAUST EMISSION CHARACTERISTICS AND VARIABILITY FOR MAINTAINED GENERAL ELECTRIC CF6-50 TURBOFAN ENGINES.	5. Report Date September 1980	6. Performing Organization Code 10/57	
7. Author(s) 10 Gary Frings	8. Performing Organization Report No. FAA-CT-80-36		
9. Performing Organization Name and Address Federal Aviation Administration Technical Center Atlantic City Airport, New Jersey 08405	10. Work Unit No. (TRAIS)	11. Contract or Grant No. 201-521-100	
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Technical Center Atlantic City Airport, New Jersey 08405	13. Type of Report and Period Covered 9 Final Rept. July - October 1979	14. Sponsoring Agency Code 1	
15. Supplementary Notes			
16. Abstract Five General Electric (GE) CF6-50 turbofan engines were tested at the GE overhaul facility in Ontario, California, to quantify and determine the variability of the exhaust emission levels. The effects of heavy maintenance on these emission levels were also studied. Only two of the engines tested actually received major maintenance. Consequently, the data collected is limited in quantity. Conclusions, observations, and recommendations are presented based on this limited data base. No correlation of exhaust emission levels and type of maintenance was possible. The exhaust emission levels of carbon monoxide (CO) and oxides of nitrogen (NO_x) have been determined; total hydrocarbon (THC) levels are not quantified. The variability of the CO and NO_x species is less than five percent, THC variability is almost 30 percent. The engine emissions did not meet the current or proposed federal standards. Ninety percent of the turbine engine exhaust emissions are produced at the idle power mode. The operational parameters for this important (from the stand-point of emission data collection) mode are vague and should be more defined. The type of fuel used for emission testing has a significant effect on the resultant exhaust emission levels.			
17. Key Words Exhaust Emissions Turbine Engine Carbon Monoxide Oxides of Nitrogen Total Unburned Hydrocarbons	18. Distribution Statement Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 53	22. Price

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol	When You Know	Multiply by	To Find	Symbol
<u>LENGTH</u>								
inches	12.5	centimeters	mm	mm	millimeters	0.04	inches	in
feet	30	centimeters	cm	cm	centimeters	0.4	inches	in
yards	0.9	meters	m	m	meters	3.3	feet	ft
miles	1.6	kilometers	km	km	kilometers	1.1	yards	yd
						0.5	miles	mi
<u>AREA</u>								
square inches	6.5	square centimeters	cm ²	cm ²	square centimeters	0.16	square inches	in ²
square feet	0.09	square meters	m ²	m ²	square meters	1.2	square yards	yd ²
square yards	0.8	square kilometers	km ²	km ²	square kilometers	0.4	square miles	mi ²
square miles	2.5	hectares	ha	ha	hectares (10,000 m ²)	2.5	acres	ac
acres	0.4							
<u>MASS (weight)</u>								
ounces	28	grams	g	g	grams	0.035	ounces	oz
pounds	0.45	kilograms	kg	kg	kilograms	2.2	pounds	lb
short tons	0.9	tonnes	t	t	tonnes (1000 kg)	1.1	short tons	(2000 lb)
(2000 lb)								
<u>VOLUME</u>								
teaspoons	5	milliliters	ml	ml	milliliters	0.03	fluid ounces	fl oz
Tbsp	15	milliliters	ml	ml	liters	2.1	pints	pt
fl oz	30	liters	l	l	liters	1.06	quarts	qt
C	0.24	-	-	-	cubic meters	0.26	gallons	gal
pt	0.47	liters	l	l	cubic meters	35	cubic feet	cu ft
qt	0.95	liters	l	l	cubic meters	1.3	cubic yards	cu yd
gal	3.8	cubic meters	m ³	m ³				
cu ft	0.03	cubic meters	m ³	m ³				
cu yd	0.76	cubic yards	m ³	m ³				
<u>TEMPERATURE (exact)</u>								
Fahrenheit	5 9 after subtracting 32	Celsius temperature	°C	°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
<u>LENGTH</u>				
in	inches	0.04	inches	in
in	centimeters	0.4	inches	in
ft	meters	3.3	feet	ft
yd	meters	1.1	yards	yd
mi	kilometers	0.5	miles	mi
<u>AREA</u>				
in ²	square inches	0.16	square inches	in ²
in ²	square centimeters	1.2	square centimeters	cm ²
in ²	square meters	2.5	square meters	m ²
yd ²	square kilometers	35	square kilometers	km ²
yd ²	hectares	1.3	hectares (10,000 m ²)	ha
mi ²	acres	35	acres	ac
<u>MASS (weight)</u>				
oz	ounces	0.035	ounces	oz
lb	pounds	2.2	pounds	lb
lb	short tons	1.1	short tons	(2000 lb)
<u>VOLUME</u>				
fl oz	fluid ounces	0.03	fluid ounces	fl oz
pt	pints	2.1	pints	pt
qt	quarts	1.06	quarts	qt
gal	gallons	0.26	gallons	gal
cu ft	cubic feet	35	cubic feet	cu ft
cu yd	cubic yards	1.3	cubic yards	cu yd
<u>TEMPERATURE (exact)</u>				
°F	32	0	32	°F
°F	40	5	40	°F
°F	80	27	80	°F
°F	120	50	120	°F
°F	160	72	160	°F
°F	200	93	200	°F
°F	222	100	222	°F
°C	0	100	0	°C
°C	20	68	20	°C
°C	40	104	40	°C
°C	80	176	80	°C
°C	120	248	120	°C
°C	160	312	160	°C
°C	200	392	200	°C
°C	222	432	222	°C

PREFACE

The author wishes to acknowledge the cooperation which was extended him by the management and personnel of the General Electric Company, Aircraft Service Operation, Ontario International Airport, Ontario, California. Their assistance to the FAA personnel during the time period of this work is gratefully appreciated.

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INTRODUCTION

DISCUSSION

PURPOSE.

The objectives of this investigation were (1) to quantify exhaust emission levels of aircraft turbine engines which had undergone extensive maintenance and (2) to determine the variability of these emission levels and the extent they were affected by various types of maintenance.

BACKGROUND.

In accordance with the Clean Air Act and the Clean Air Amendments of 1970 (reference 1), the Environmental Protection Agency (EPA) established aircraft turbine engine emission standards. The Department of Transportation (DOT) and, specifically, the Federal Aviation Administration (FAA) was charged with promulgating regulations enforcing these standards. Changes to these standards (40 CFR, part 87, reference 2) have been drafted and are being evaluated, but there remains a requirement to quantify the emission levels of turbine engines throughout their operational life. To meet this requirement the emission levels of newly manufactured engines have been and still are being investigated. Present data on the effects of heavy maintenance and "on-condition" maintenance on turbine engine emission levels are limited. In order to formulate regulations for control of aircraft exhaust emissions and to establish the requirements for redemonstration of compliance with EPA standards after initial certification, the FAA must determine the effects of such maintenance on turbine engine emission levels. This report provides emission data from General Electric (G.E.) Company CF6-50 turbofan engines which were tested at the G.E. Aircraft Service Operation (ASO) maintenance and repair facility located at Ontario International Airport, Ontario, California.

METHODOLOGY.

The turbine engine exhaust constituents which were measured included carbon monoxide (CO), carbon dioxide (CO₂), total hydrocarbons (THC), oxides of nitrogen (NO_x), and oxygen (O₂). It was determined that three engine types would be tested: the Pratt and Whitney JT8D-7A, JT9D-7A, and the G.E. CF6-50. These engines were selected on the basis of their high in-use rate, expected long term service, and availability of new engine emission data. This document reports the CF6-50 test results. Separate documents report the results of testing of the other two engines.

A contractual effort with G.E. Company was initiated wherein they supplied the engine, test cell facilities, support personnel, and necessary engine documentation. The FAA provided the emission measuring equipment and support personnel for its operation and maintenance. Five of the ten scheduled engine emission tests were conducted at the ASO Ontario facility. The lack of engine availability and closing of the test cell for major facility upgrading during the scheduled test period necessitated early termination.

DESCRIPTION OF ENGINE.

The CF6-50 is a high bypass ratio engine. The high fan air bypass ratio of 4.4 yields a rating of 50,000 pounds thrust (F_g); 77 percent of this thrust rating is generated by the mass flow through the fan stage. The core engine is an axial flow design. A four-stage low-pressure compressor (N₁) (the fan being the first stage) is driven by a four-stage low pressure turbine. The inlet guide vanes and first six stages of the 14 stage high pressure compressor (N₂) have variable geometry vanes. Two turbine stages drive N₂. The

overall pressure ratio is approximately 30. The combustor is an annular design. Both the main and angle gear boxes and engine accessories are mounted at the bottom of the fan case (reference 3), figures 1 and 2. Table 1 lists average corrected engine parameters encountered during testing.

DESCRIPTION OF TEST PROCEDURE.

Engine performance/acceptance testing and emission sample testing were conducted separately. After repair, each engine was installed in the test cell and the normal performance/acceptance test runs were conducted. These procedures included fluid leak checks, main engine control trimming, dynamic balancing of the fan stage, and a complete set of engine runs to check performance. After the satisfactory completion of these checks, the emission sampling probe was attached to the dedicated exhaust nozzle which had been previously modified for this purpose. The engine was then run at the power conditions listed in table 2. At the completion of the stabilization time at each power condition, a complete set of engine performance and emission data was recorded simultaneously. The stabilization times listed in table 2 were required for the engine emissions to achieve equilibrium. To more clearly define the emission levels, mode 2 (idle + 500 RPM-N₁) was included into the standard EPA landing/take-off (LTO) cycle. Mode 2 was not used in the final emission EPA parameter (EPAP) calculations.

DESCRIPTION OF MAINTENANCE PROCEDURES.

The ASO Ontario operation is the main facility for the repair of G.E. engines. Located here is all the necessary equipment and personnel for the complete inspection, service, repair, modification, and overhaul of CF6 engines. The CF6-50 is a modular engine. Much of the maintenance, such as turbine and compressor replacements can be

accomplished in the field; therefore, most engines coming into this facility would be in need of a major overhaul. This was not the case in three of the five engines tested under this program. The ASO Ontario facility is basically a "job shop." Engines are sent to this facility by various airlines on an "as needed" basis. Consequently, the facility cannot schedule when the engines come into the shop. During the period of testing, two of the five engines tested received complete overhauls, two engines had accrued minimal time-since-new (TSN), and one engine received no maintenance (table 3). This last engine was a G.E. owned lease-pool engine which came into the shop for turbine development work. An incoming baseline performance and emission test was accomplished on this engine. Unfortunately, a post turbine refurbishment emission test to determine the effects of turbine maintenance on exhaust emissions could not be accomplished on this engine as planned, due to the termination of the project.

DESCRIPTION OF TEST CELL.

The CF6 test cell at ASO Ontario was used for all performance and exhaust emission testing (figure 3). This is a sea level test cell incorporating inlet and exhaust sound suppression. A 3-inch diameter hole was drilled into the test cell wall through which the emission sample line was routed. The engines were mounted to a "clam shell" type thrust measuring stand, peculiar to the CF6 family of engines (figure 4). The "clam shell" incorporates the fan thrust reverser mechanism. Engine instrumentation was typical of that required for production engine performance testing. All engine data were manually recorded and concurrently fed into a data acquisition system which processed the data onto punched tape. The tape was subsequently fed into the main G.E. computer located in Evendale, Ohio via dedicated lines. Processed engine data are returned to ASO Ontario usually on the same day.

TABLE 1. AVERAGE CORRECTED ENGINE PARAMETERS FOR FIVE ENGINES

	<u>Thrust Specific Fuel</u>	<u>Fuel Flow (lbs/hr)</u>	<u>Consumption (lbs/hr/lb)</u>	<u>Core Air Flow (lbs/sec)</u>	<u>Exhaust Gas Temperature (°R)</u>	<u>N₁ (rpm)</u>	<u>N₂ (rpm)</u>
Idle	1787.4	1357.0	0.7597	37.8	1189.0	853.4	6316.2
T. O.	48061.6	18878.3	0.3928	280.6	1967.7	3744.9	10102.7
85 %	41284.0	15784.6	0.3824	254.2	1863.6	3523.3	9836.9
30 %	14119.2	5123.4	0.3629	130.2	1366.8	2306.3	8594.8
Idle +	1783.2	1321.5	0.7414	37.9	1172.2	851.9	6309.4
	4531.2	2176.0	0.4805	63.8	1175.9	1354.5	7515.2

TABLE 2. CF6-50 TEST CYCLE

<u>Mode No.</u>	<u>Test Mode</u>	<u>N₁ (rpm)</u>	<u>Power (% Rated)</u>	<u>Stabilization Time (minutes)</u>
1	Idle Out	853.4	3.5	20
2	Idle + 500 rpm N ₁	1354.5	9.5	5
3	Takeoff	3744.9	100.0	5
4	Cruise	3523.3	85.0	5
5	Approach	2306.3	30.0	5
6	Idle In	851.9	3.5	10

TABLE 3. MAINTENANCE SUMMARY OF CF6-50 ENGINES

<u>Test Number</u>	<u>Engine Serial No. (ESN)</u>	<u>Plotting Symbol</u>	<u>Date</u>	<u>Time Since New (TSN) (hr)</u>	<u>Time Since Overhaul (TSO) (hr)</u>	<u>Type Of Maintenance</u>
1	455-490	□	7/19/79	100	N/A	Oil line replacement in turbine mid-frame
2	517-111	○	8/04/79	11548	0	Complete overhaul
3	517-113	◇	8/09/79	11136	0	Complete overhaul
4	455-254	△	8/14/79	6260	3000	None, incoming check
5	455-436	✗	9/30/79	5	N/A	P and D valve replacement, main engine control replacement

TABLE 4. AMBIENT TEST CONDITIONS

Compressor Inlet Temperature (CIT) (T_{t2} °F)	Compressor Inlet Pressure (CIP) (P_{t2} in/Hg)	Humidity (grains H_2O /lb dry air)
Minimum	74.4	28.901
Maximum	88.9	29.037

TEST CONDITIONS.

All CF6-50 turbine engine exhaust emission tests were conducted between July 19, 1979, and September 30, 1979. Table 4 lists the minimum and maximum ambient conditions encountered during tests.

EMISSION SAMPLING SYSTEMDESCRIPTION OF SAMPLING PROBE.

The emission sampling probe utilized for CF6-50 testing is an FAA developed design (reference 4). The probe consists of a tube section in the shape of a diamond (figures 5 and 6). Each leg of the diamond contains three evenly spaced sampling holes of equal diameter. The sampling tube is secured to a backup structure and positioned on the exhaust nozzle rim with four equispaced clevis mounting pads (figure 7). The entire probe mechanism is secured to the engine using six equispaced tensioning rods. One end of these rods is attached to a torsional support ring on the probe clevis pieces; the other end of the rods is secured to six mounting pads which are tack-welded to the CF6-50 exhaust nozzle. Thermal expansion of the exhaust nozzle is taken up by compression springs incorporated into the tensioning rods. Rapid mounting (usually less than 20 minutes) of the probe to the engine was possible by utilizing this mechanism.

The probe was located 10 inches axially downstream of the exit plane of the exhaust nozzle. Based on prior development work (reference 4) this location provides a representative sample of all emission species while providing a minimal thrust loss, due to its location in the exhaust plume.

The measured thrust loss, due to the probe installation at the takeoff power condition, averaged 1,715 pounds for the five engines tested. Actual developed thrust, however, should not have been significantly affected by the probe. For the purposes of this program, 100 percent power was considered to be that thrust which was generated by the engine with the probe attached to the exhaust nozzle. The 30 and 85 percent power conditions of the LTO cycle are then calculated accordingly.

DESCRIPTION OF MOBILE EMISSION RESEARCH FACILITY (MERF).

The MERF, a self-contained, sound-attenuated, and environmentally controlled mobile emission measurement laboratory was used for all CF6-50 turbine engine exhaust emission testing (figures 8 and 9). Commercially available power was used in lieu of the on-board generators. Calibration and operating gas cylinders are carried on-board (table 5, figure 10). A heated external sample line transports the emission sample is routed to the

TABLE 5. MERF CALIBRATION GASES

<u>Calibration Mode</u>	<u>CO (ppm)</u>	<u>CO₂ (%)</u>	<u>C₃H₈ (ppm)</u>	<u>NO (ppm)</u>	<u>O₂ (%)</u>	<u>BALANCE GAS</u>
Span 1	100	1	10	25	--	N ₂
Span 2	400	3	50	100	--	N ₂
Span 3	1000	5	500	250	20.9	N ₂
Zero			Nitrogen Gas To All Analyzers			

the analyzers through heated lines (figure 11). The CO/CO₂ sample is routed through a gas dryer. The CO₂ analyzer is a Beckman model 864 non-dispersive infrared (NDIR) unit calibrated on three ranges at 0-5, 0-3, and 0-1 percent full scale (figure 12). The CO analyzer is a Beckman model 865 NDIR unit calibrated on three ranges at 0-1,000, 0-400, and 0-100 parts per million (ppm) volume full scale. The THC analyzer is a Beckman model 402 flame ionization detector unit calibrated on four ranges at 0-10, 0-50, 0-100, and 0-500 parts per million propane (C₃H₈). This analyzer has been modified to improve its operation. These modifications are described in detail in reference 5. The NO_x analyzer is a Beckman model 951H_x atmospheric pressure, heated, chemiluminescent analyzer calibrated on five ranges at 0-10, 0-25, 0-100, 0-250, and 0-1,000 ppm full scale. The O₂ analyzer is a Beckman model OM-11 medical unit with a polarographic sensor. The advanced sensor and amplification system combine to make this analyzer an extremely fast, responding, and highly accurate instrument. It is calibrated up to 20.9 percent oxygen.

The MERF data acquisition system, based on a Hewlett-Packard 9830B calculator, receives the analyzer output and converts this information to actual emission concentrations which are printed out after each data point (figure 13). Communications between the

MERF operator and the engine operator's station is provided by a David Clark Company model U3400 utility intercom system.

A more detailed description of the MERF systems may be found in reference 6.

MERF OPERATION.

A multipoint calibration on each range of the MERF instrumentation is accomplished at least 30 days before testing and each time major modifications or repairs are performed on the instruments (appendix A).

A detailed startup, calibration, and operation procedure checklist for the MERF is included in this report (appendix B).

The MERF carries a full complement of working gases (table 5) including:

Zero gas—99.999 percent pure nitrogen

FID fuel—40 percent hydrogen, 60 percent helium (less than 1 ppm THC)

FID air—hydrocarbon free (less than 0.1 ppm THC)

100 percent oxygen—for 951H_x ozonizer

All calibration gases are carried in treated aluminum cylinders. CO/CO₂/C₃H₈/O₂-N₂ are carried as multi-component mixtures in a single cylinder.

TABLE 6. EPAP * EMISSION LEVELS

<u>ESN</u>	<u>THC</u>	<u>CO</u>	<u>NO_x</u>
455-490	5.755	11.239	8.756
517-111	5.678	10.835	8.591
517-113	7.556	11.220	8.536
455-254	4.392	10.979	8.114
455-436	3.710	10.260	8.428
Mean (\bar{x})	5.418	10.907	8.485
Standard Deviation (σ)	1.476	0.399	0.239
Standard Deviation (%)	27.3	3.66	2.81
$\bar{x} \div$ Federal Standard	6.77	2.54	2.83

* lbs pollutant/1,000 lbs thrust

All calibration gases have a blend tolerance of +0/-5 percent, and an analytical accuracy of ± 1 percent of true value for concentrations greater than 100 ppm and ± 2 percent of true value for concentrations less than 100 ppm. Before a new calibration gas is placed into operation it is compared to existing calibration curves and National Bureau of Standards (NBS), Standard Reference Material (SRM) gases. All NBS SRM cylinders are less than 1 year old.

The MERF instrumentation was calibrated prior to engine start and again at the conclusion of the test. During all engine starts and shut-downs the sample line was reverse flushed with nitrogen gas to preclude any fuel from entering the sample train and contaminating the system.

ANALYSIS

The mean (\bar{x}) emission levels and their variability (one standard deviation σ) expressed in terms of EPAP's for the CF6-50 engines tested are listed in

table 6 and represented in bar graph form in figures 14, 15, and 16. The emission levels are further represented in terms of Emission Index (pounds of pollutant per 1,000 pounds of fuel) in figures 20, 21, and 22. It should be noted that both the engine parameters and emission data are plotted against N_1 . Since 77 percent of the thrust is generated by the fan, N_1 rotor speed is the power determining parameter.

The low variability of the CO and NO_x species, 3.66 percent and 2.67 percent, respectively, figures 14, 16, and 20 indicate good engine-to-engine agreement of the emission data. This trend is reinforced by the low variability of the engine performance and operating data (appendix D) and is graphically represented in figures 17, 18, and 19. These data indicate that maintained CF6-50 engines tested at the same power conditions will exhibit very similar emission characteristics.

This assumption does not apply to the THC emission levels which exhibit a large variability, 27.3 percent. This

large variability may be attributed to the fact that the engines which were tested represented a broad spectrum in the operational life of these engines from almost new (5 hours TSN) to high time (3,000 hours time-since-overhaul, TSO) to completely overhauled (0 hours TSO, 11,000 hours TSN). This engine-to-engine variability of the THC species does not appear to follow any specific trend. The high time (engine serial number (ESN) 455-254) and the almost new (ESN 455-436) engines produced relatively low THC emission levels. One overhauled (ESN 517-111) and one relatively new engine (ESN 455-490) produced average THC emission levels. The second overhauled engine (ESN 517-113) produced the highest THC emission levels.

The variability of the THC species produced by these engines cannot be attributed to different engine operating parameters or emission instrumentation.

Emission data on newly manufactured CF6-50 engines has been supplied to the FAA by the manufacturer under contract number DOT-FA78WA-4207. A comparison of the new engine mean emission levels and the mean emission levels of this report shows that the data are very similar for all emission species. The primary difference between the two sets of data is the aforementioned large THC variability, a characteristic not shared by the new engine data.

Two groups of new engines were tested for emissions by the manufacturer. One group of 12 engines was run on JP-4 grade turbine fuel, six other engines were run using Jet-A grade turbine fuel. The manufacturer reported an increase in THC-EPAP emission levels of 59 percent, CO-EPAP 22 percent, and NO-EPAP 5 percent when using Jet-A rather than JP-4. A comparison of the EPAP emission levels of this report using JP-4 fuel with the aforementioned manufacturers data using Jet-A fuel shows an increase of 50, 30, and zero percent, respectively. The close agreement of

the EPAP emission levels (59 percent versus 50 percent, 22 percent versus 30 percent, 5 percent versus 0 percent) between the manufacturer's effort and this effort indicate that, had this emission testing been conducted utilizing Jet-A fuel, the emission levels reported herein would necessarily be higher by a corresponding amount.

An examination of figures 20 and 21 shows that the idle mode is the largest contributor to the gross CO and THC pollutant levels. Well over 90 percent of the emissions, on a mass pollutant basis calculated over the LTO cycle, are produced at the idle mode. This condition is understandable since a typical turbine engine does not operate very efficiently at this power condition. Engine efficiency increases rapidly and emission levels decrease rapidly as the engine is accelerated from idle up to power. Due to the extremely steep gradient of the CO and THC emission levels at the idle power condition, a more precise definition of the idle mode is necessary to insure that all future emission testing is conducted in a uniform manner.

GENERAL COMMENTS.

1. G.E. CF6-50 turbine engine exhaust emission testing was performed at the G.E. turbine engine repair and service facility located at Ontario, California.
2. Using the LTO test cycle, EPAP emission levels and their variability for five CF6-50 engines have been determined.
3. Two engines tested received major overhauls; two received relatively minor maintenance; one engine received no maintenance.
4. All engine tests were conducted using JP-4 turbine fuel. This is the fuel normally used at the Ontario facility. Appendix C contains the analysis of fuel used during testing.

5. All emission data were corrected for temperature and humidity effects according to reference 7.

OBSERVATIONS.

Although not specifically a part of the stated objectives, these observations are, in the author's opinion, of significant importance to warrant presentation.

1. The five CF6-50 engines tested did not meet the Environmental Protection Agency (EPA) turbine engine exhaust emission standards as published in the Federal Register (CFR) of July 17, 1973, which are the standards in effect at this writing. Nor do they meet the standards as proposed in the CFR of March 24, 1978. Both standards are exceeded by large margins (see table 6).

2. Based on the availability of turbine engine exhaust emission data from newly manufactured CF6-50 engines the following is presented:

a. Emission levels of newly manufactured engines and maintained engines are very similar. A comparison of the EPAP calculations verifies this fact.

b. The grade of turbine fuel used for emission testing will have a significant effect on the emission levels. There is a considerable increase of emission levels when Jet-A grade fuel is used instead of JP-4. If broader specification jet fuels are used, an increase in the emission levels should be expected.

CONCLUSIONS

A restatement of the objectives is in order. In regard to maintained CF6-50 engines, the objectives of this effort were to quantify and determine the

variability of exhaust emission levels and also determine to what extent these emission levels are affected by different types of maintenance. Due to the fact that only two of the five engines tested for exhaust emissions actually received any major maintenance, these objectives could not be totally achieved. With this in mind the following conclusions are presented:

1. No correlation of exhaust emission levels and type of maintenance performed on the engine was possible due to the limited number of maintained engines which were tested. Of the two overhauled engines, engine serial number (ESN) 517-111 produced "average" emission levels for all three species while the other overhauled engine ESN 517-113 produced the highest total hydrocarbon (THC) levels of the five engines tested.

2. The exhaust emission levels of maintained CF6-50 engines could not be totally quantified for the THC species. Carbon monoxide (CO) and oxides of nitrogen (NO_x) species have been quantified.

3. The Environmental Protection Agency Parameter (EPAP) variability of the exhaust emission levels for these engines is low (less than 5 percent) for the CO and NO_x species, and high for the THC species (almost 30 percent). These percentages are based on an analysis which considers all five engines. This is a valid procedure based on the excellent agreement (low variability) of the CO and NO_x species.

RECOMMENDATION

The idle mode for turbine engines should be more clearly defined by the engine manufacturer. This mode is the single largest contributor of CO and THC species in the EPAP calculations.

REFERENCES

1. Clean Air Amendments of 1970, Public Law 91-604, 91st Congress, H.R. 17255, December 31, 1970.
2. Control of Air Pollution from Aircraft and Aircraft Engines, Federal Register, Volume 38, Number 136, Part II, July 17, 1973.
3. CF6 High Bypass Turbofan, Customer Handbook, General Electric, Aircraft Engine Group, 1970, Revised 1972.
4. Slusher, G. R., Emission Sample Probe Investigation of a Mixed Flow JT8D-11 Turbofan Engine, FAA Technical Report FAA-RD-77-175, July 1978.
5. Aircraft Piston Engine Exhaust Emission Symposium, National Aeronautics and Space Administration Publication NASA CP-2005, September 1976.
6. Becker, E. E., Frings, G., Cavage, W. C., Exhaust Emission Characteristics and Variability for Pratt and Whitney JT8D-7A Gas Turbine Engines Subjected to Major Overhaul and Repair, FAA Technical Report FAA-NA-79-53, September 1980.
7. Allen, L., Slusher, G. R., Ambient Temperature and Humidity Correction Factors for Exhaust Emissions from Two Classes of Aircraft Turbine Engines, FAA Technical Report FAA-NA-76-16, October 1976.
8. Tyrrell, James, Aircraft Engine Emissions Measurement System, Calibration Procedure, FAA NAFEC Letter Report, August 1978.

FIGURE 1. CF6-50 TURBOFAN ENGINE (LEFT FRONT)



FIGURE 2. CF6-50 TURBOFAN ENGINE (LEFT REAR)

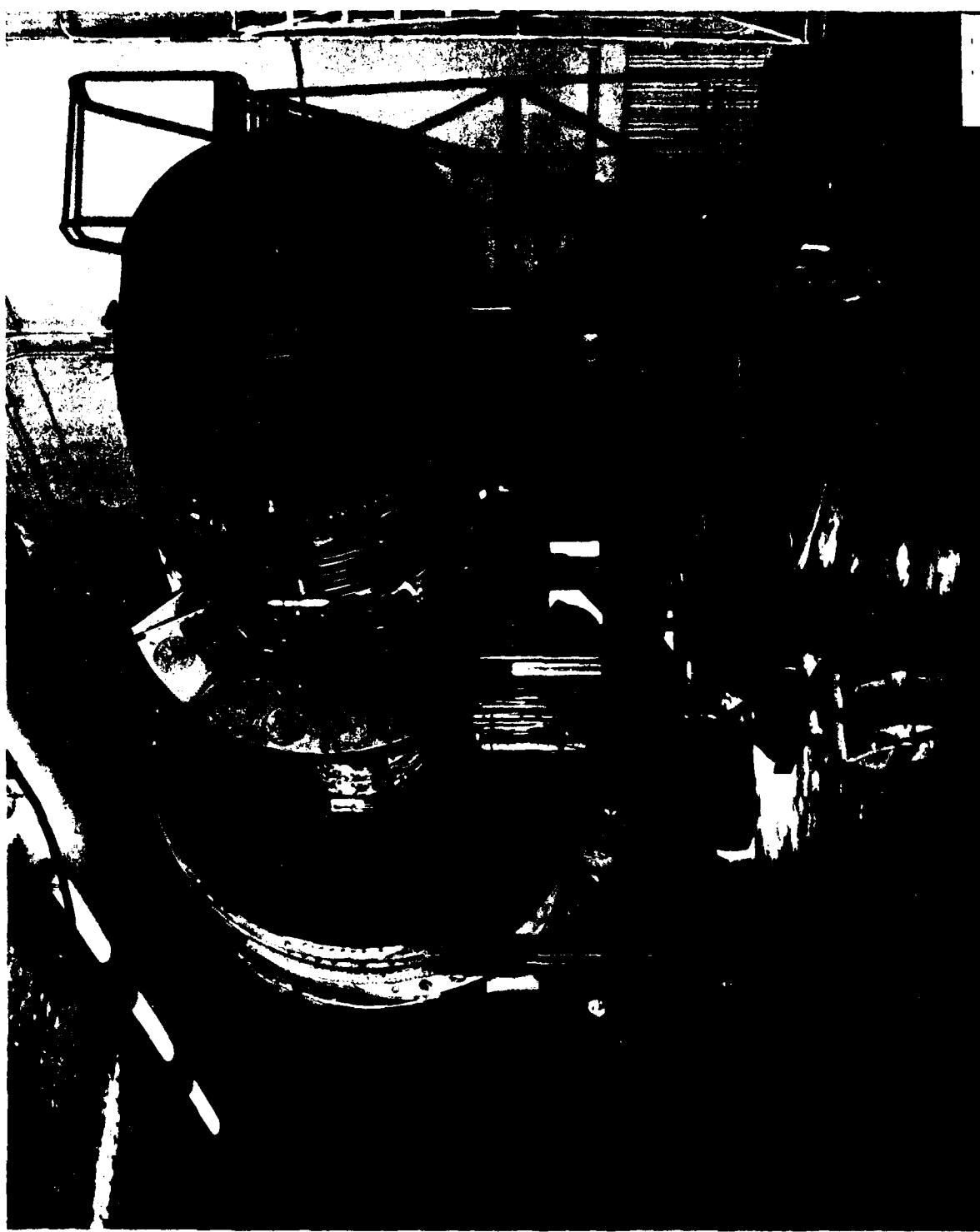
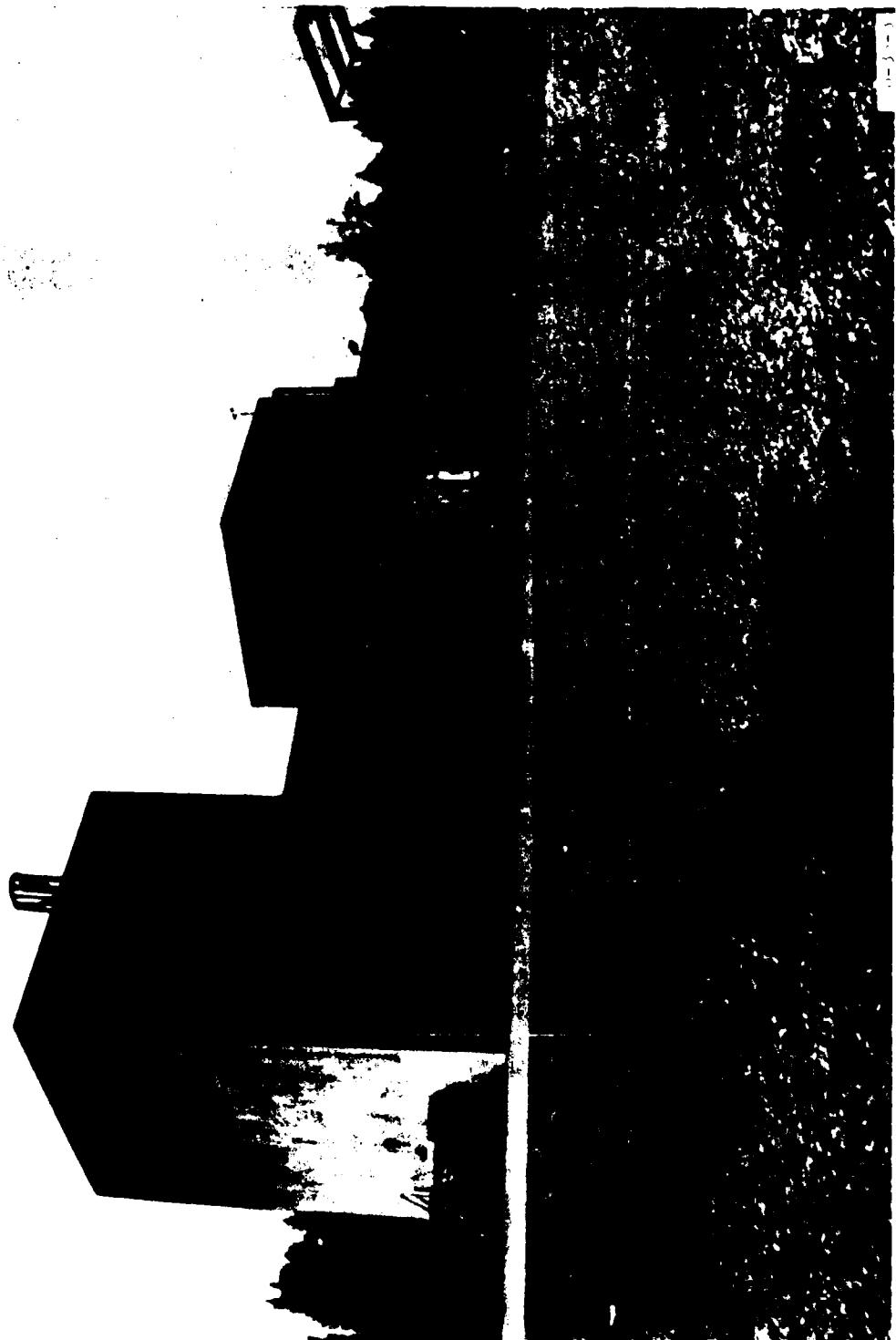


FIGURE 3. CF6 TEST CELL



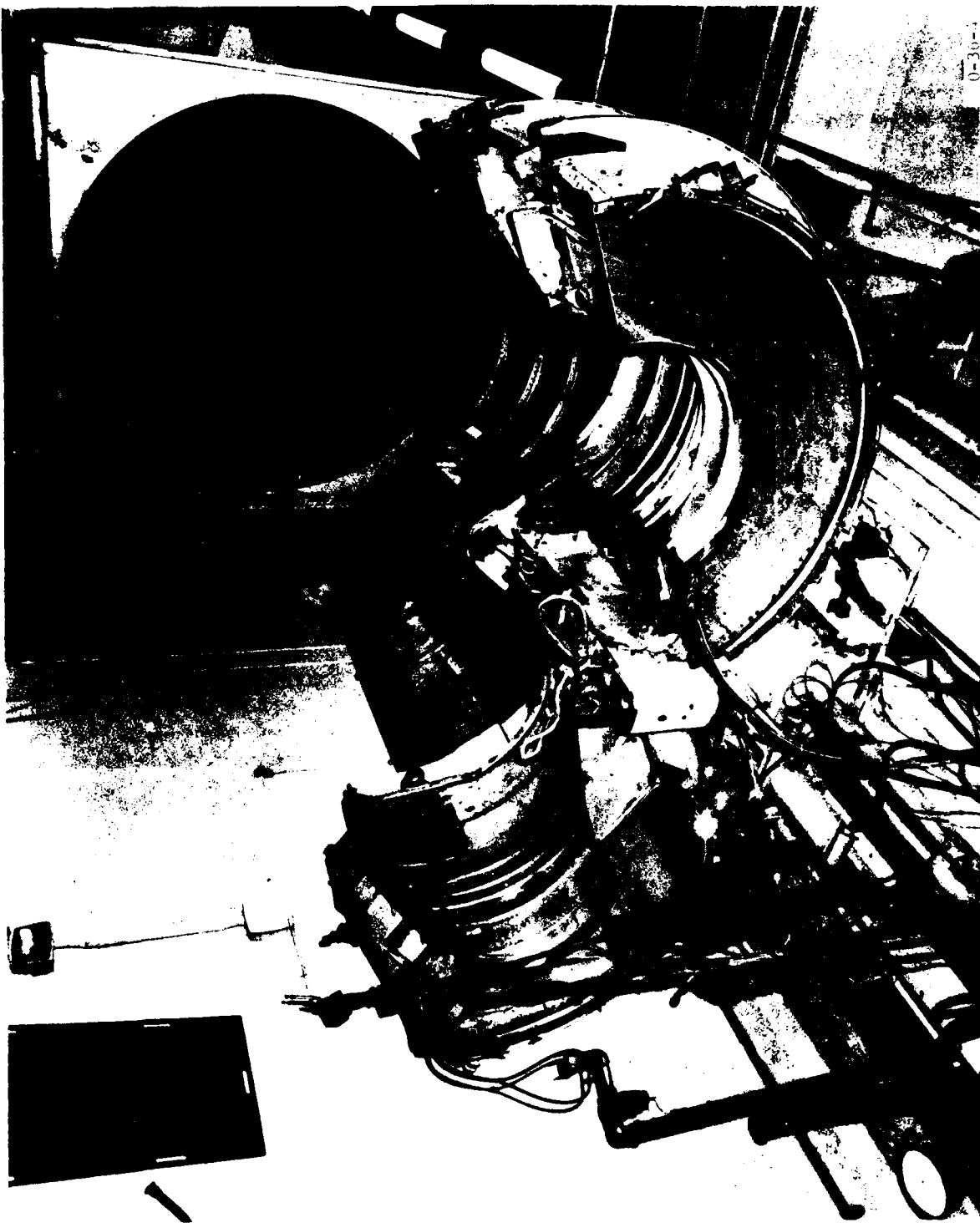


FIGURE 4. CF6 ENGINE TEST STAND AND FAN REVERSER

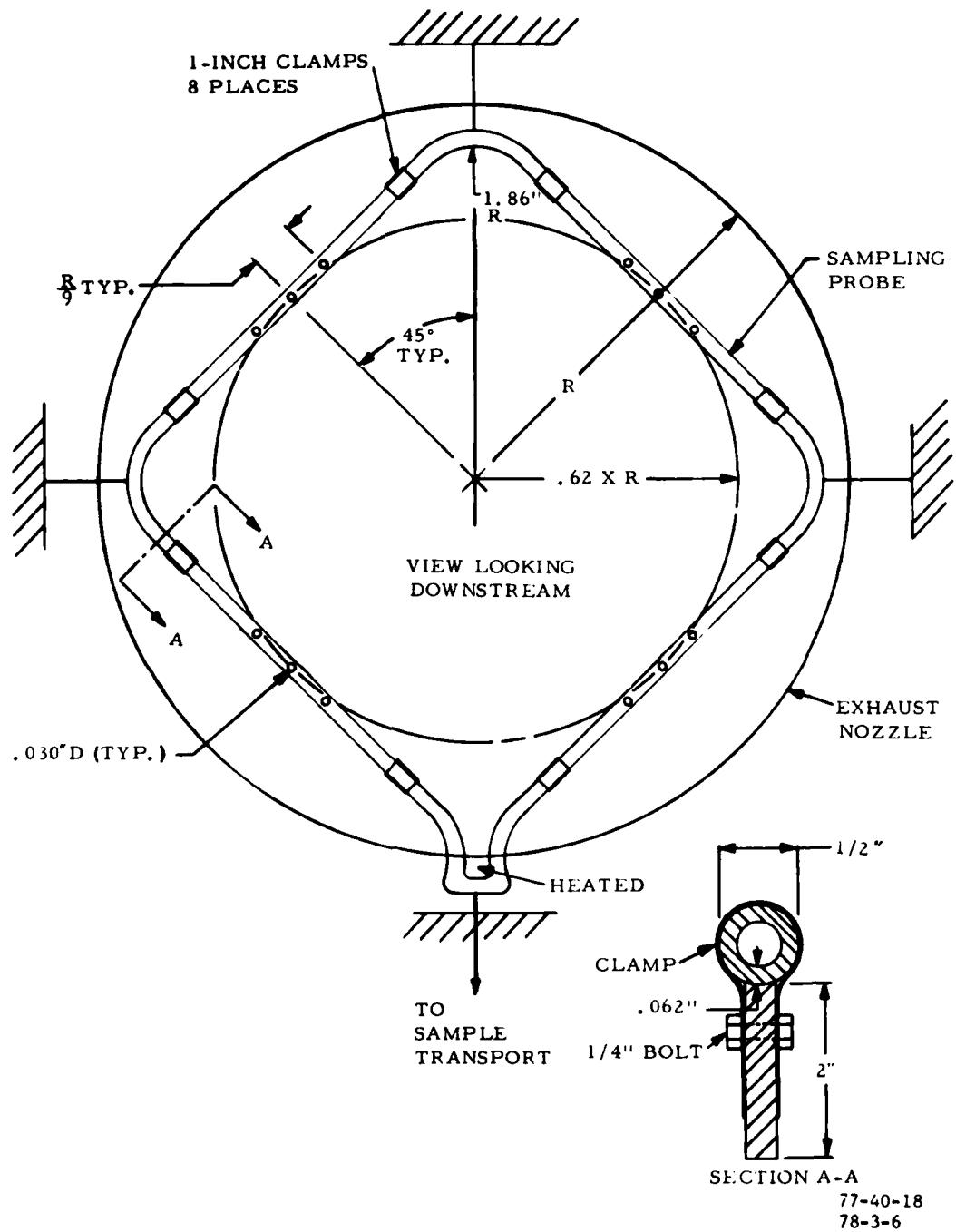
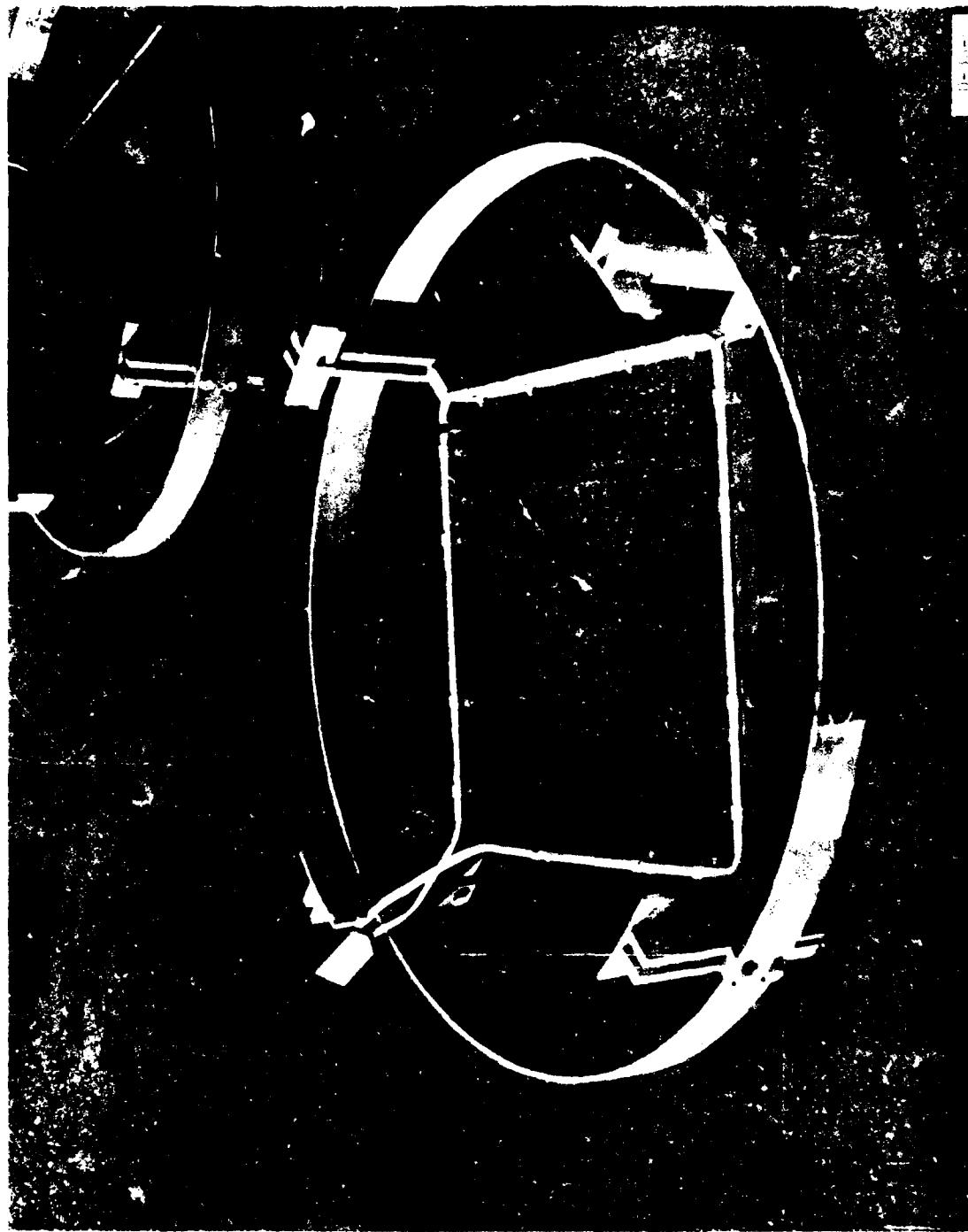


FIGURE 5. EMISSION SAMPLING PROBE SCHEMATIC

FIGURE 6. EMISSION SAMPLING PROBE SCHEMATIC



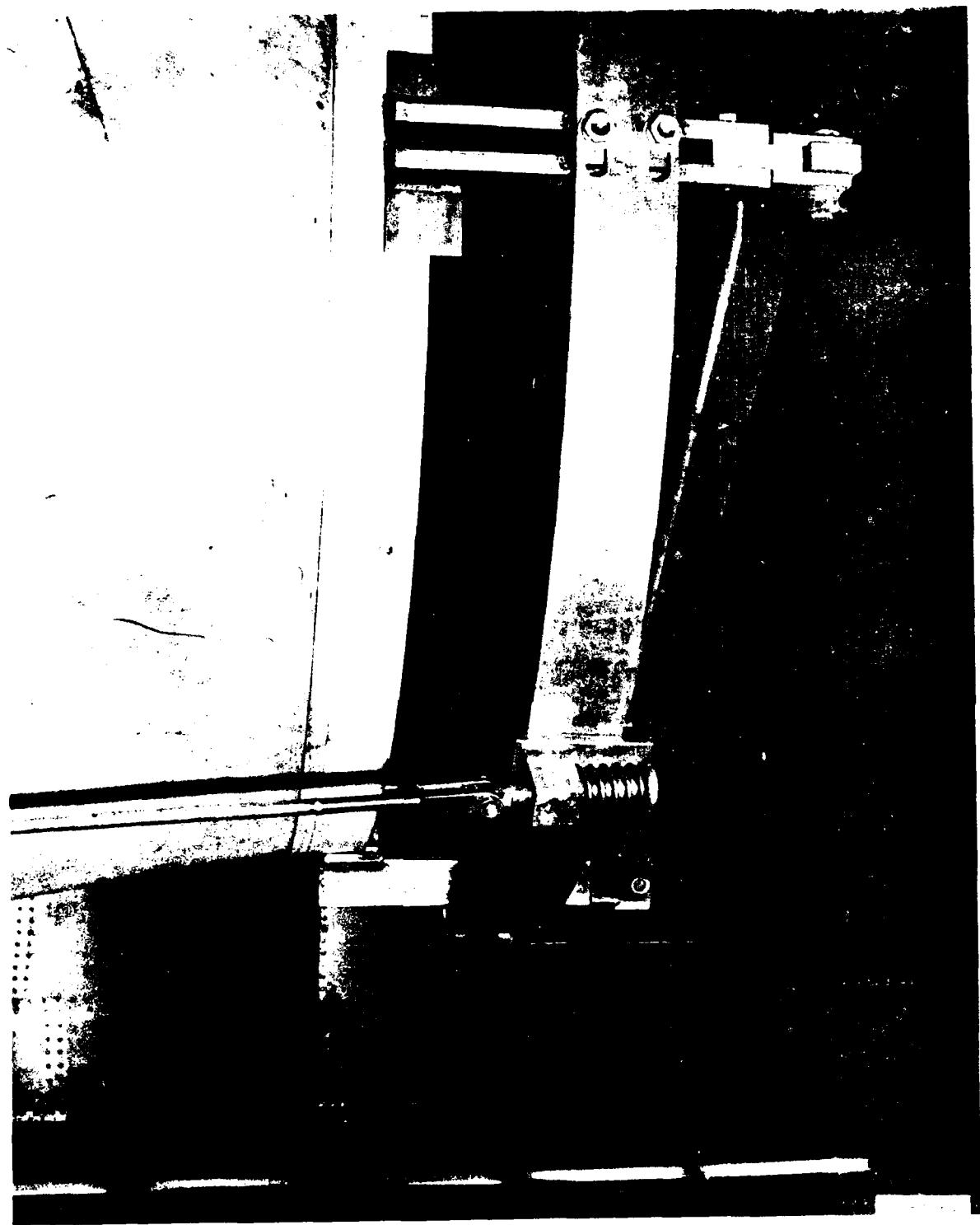


FIGURE 7. PROJECTOR AND FILM HOLDER

0-36--o



FIGURE 8. MOBILE EMISSION RESEARCH FACILITY (MERF)

0-30-9

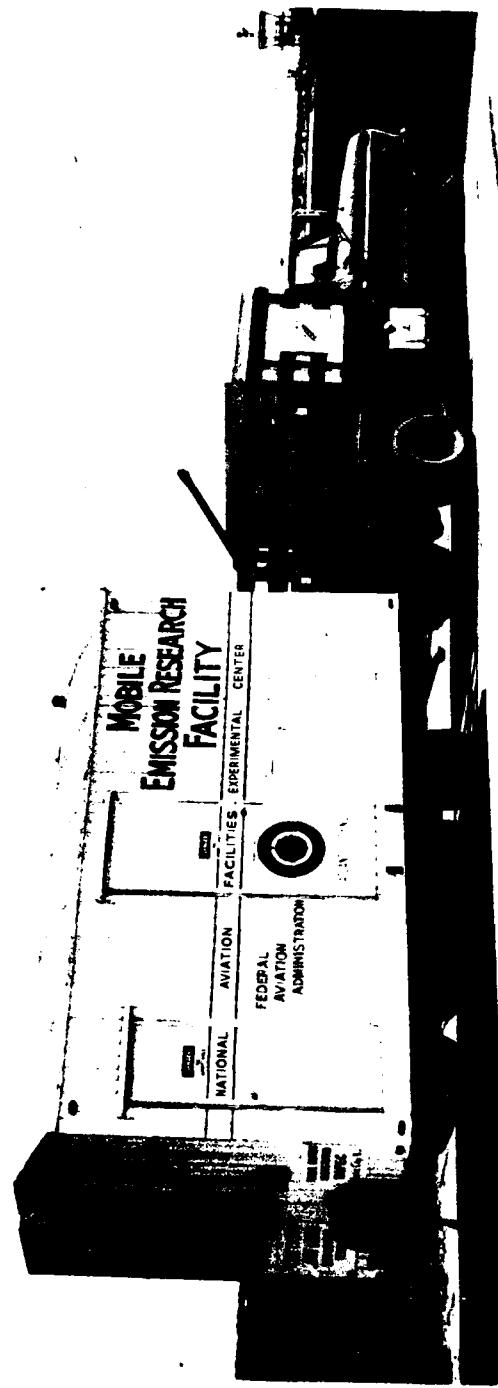


FIGURE 9. MERF AND TOW VEHICLE



30-36-10

FIGURE 10. MERC CALIBRATION GAS CYLINDER STORAGE AREA

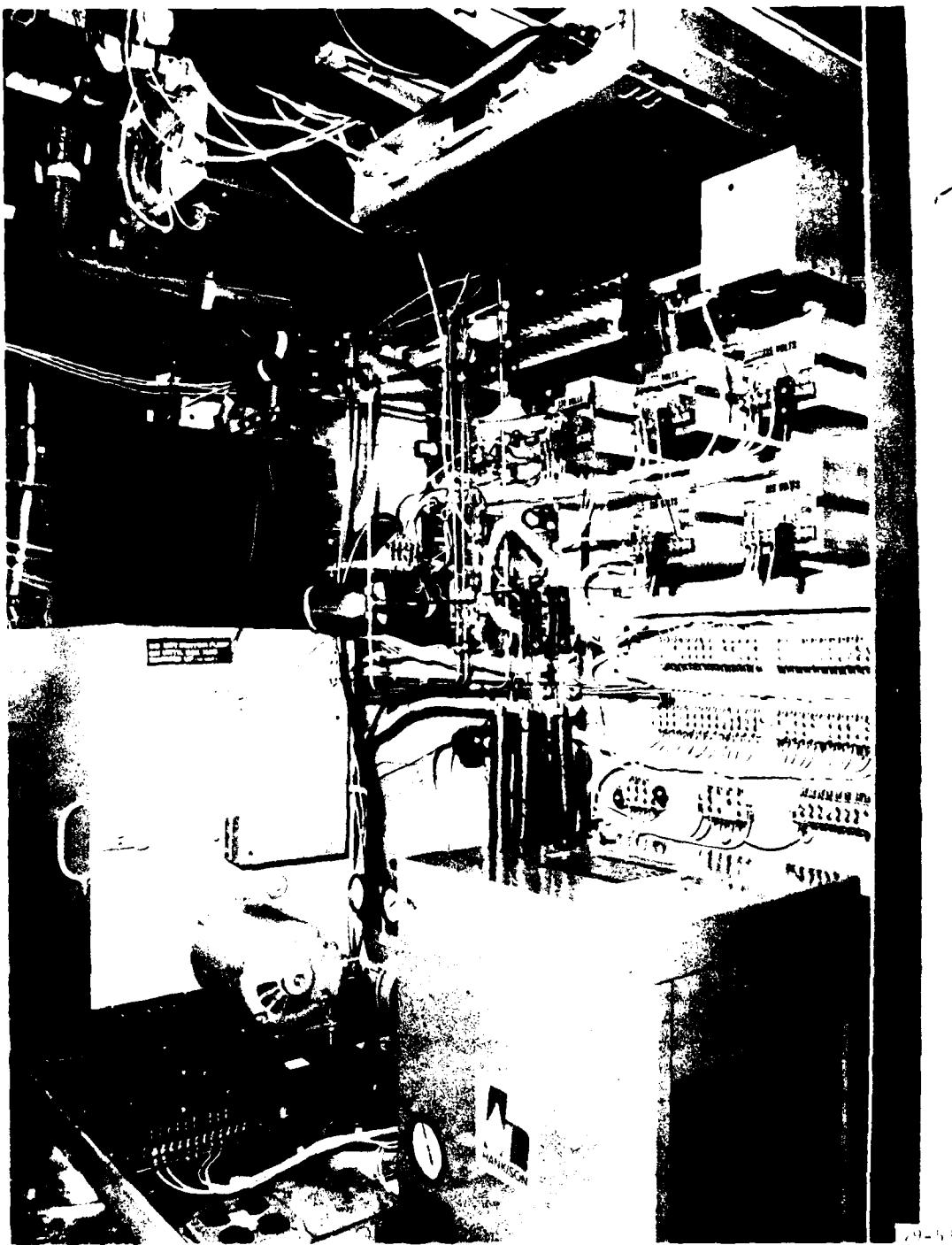


FIGURE 11. MERF INSTRUMENTATION (REAR PANEL)

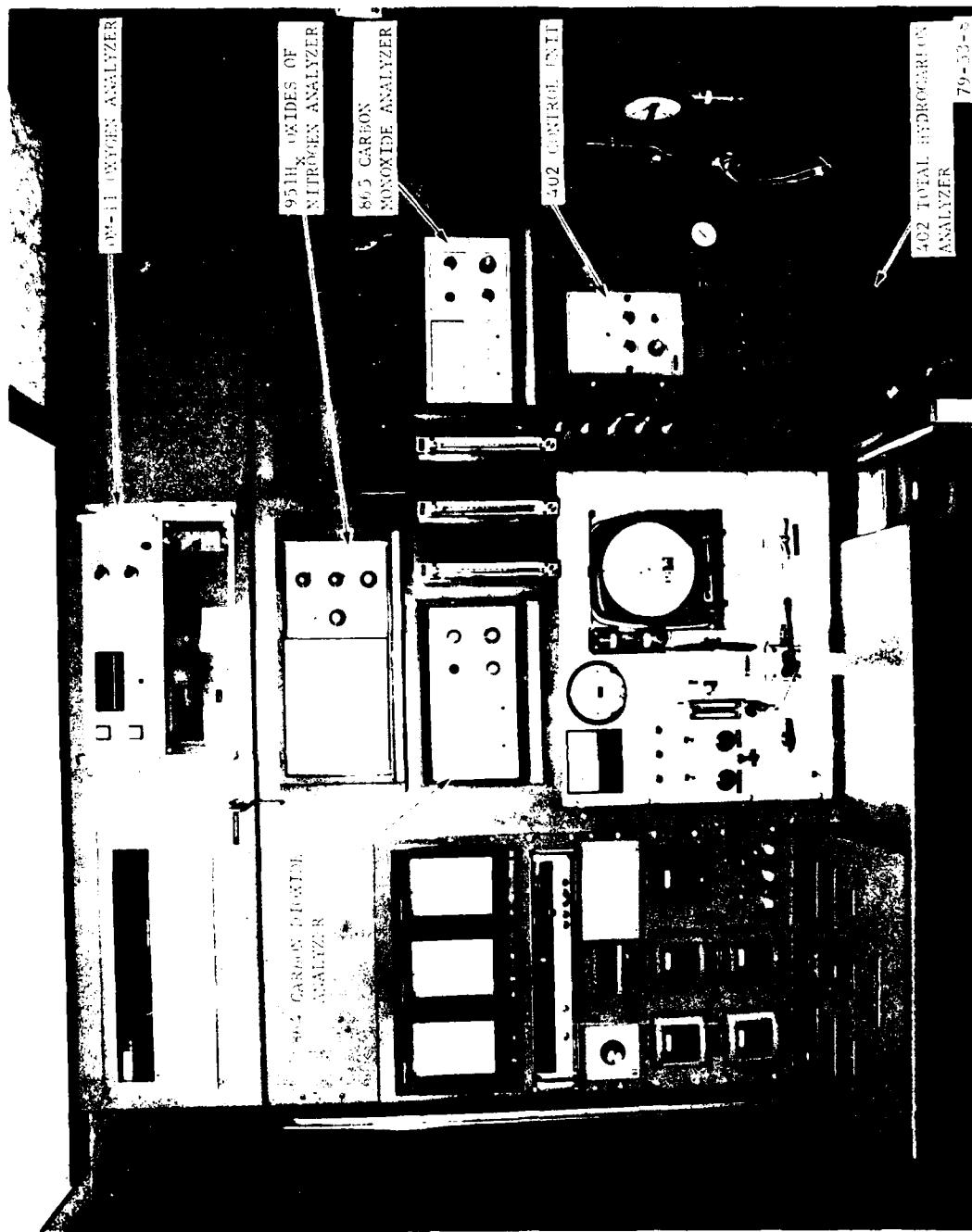


FIGURE 12. MERF INSTRUMENTATION (FRONT PANEL)



FIGURE 13. HEWLETT-PACKARD 9830 CALCULATOR (PART OF DATA ACQUISITION SYSTEM

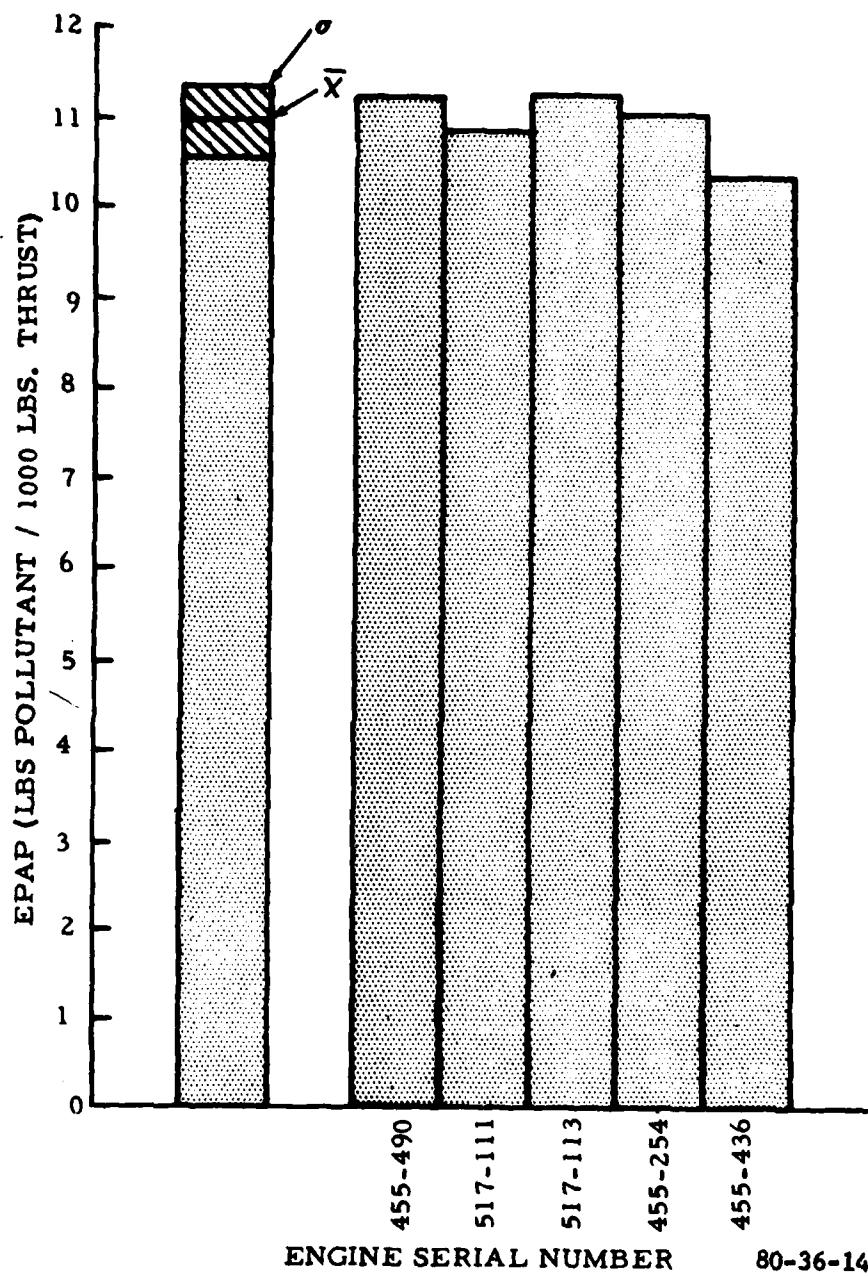


FIGURE 14. CARBON MONOXIDE EMISSION LEVELS

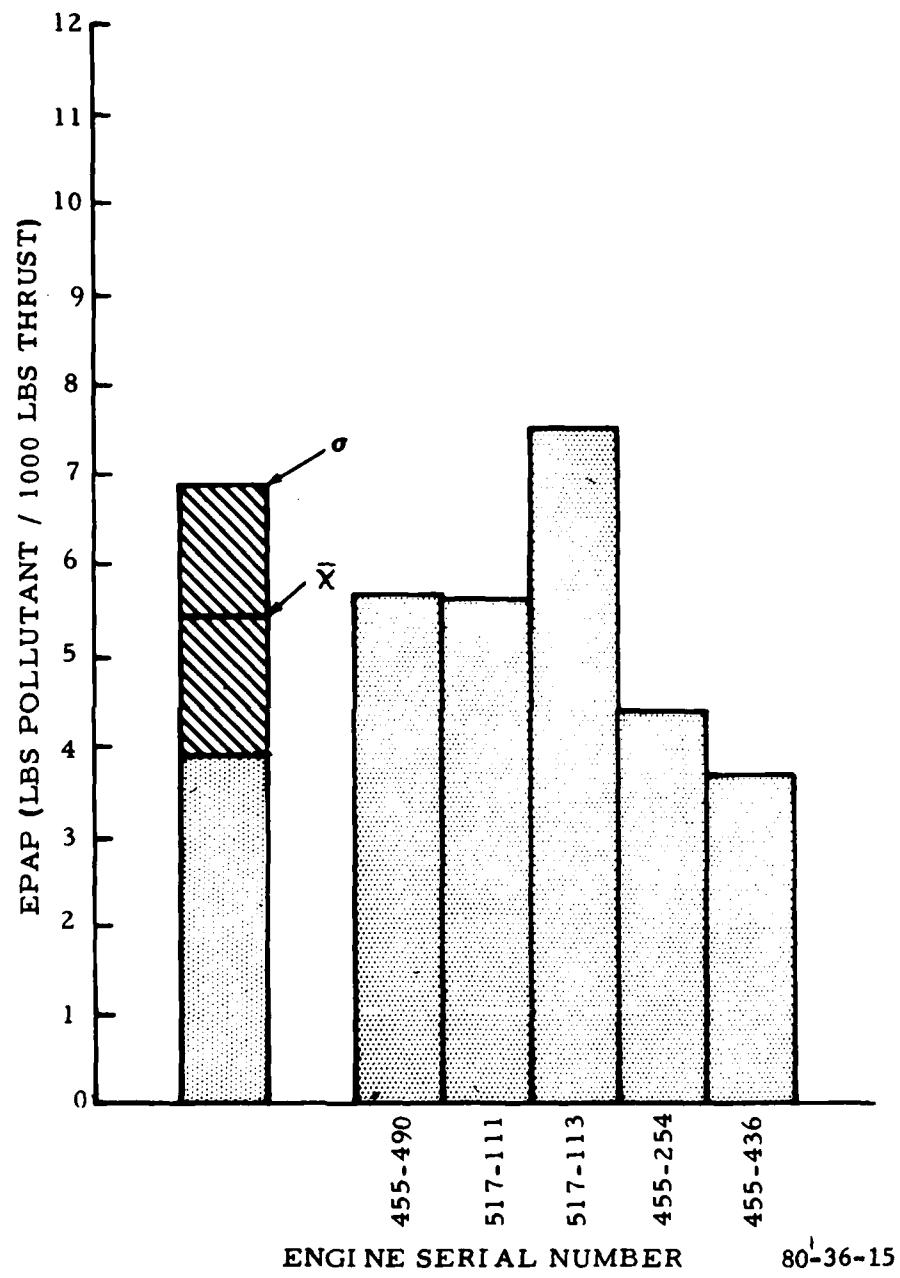


FIGURE 15. HYDROCARBON EMISSION LEVELS

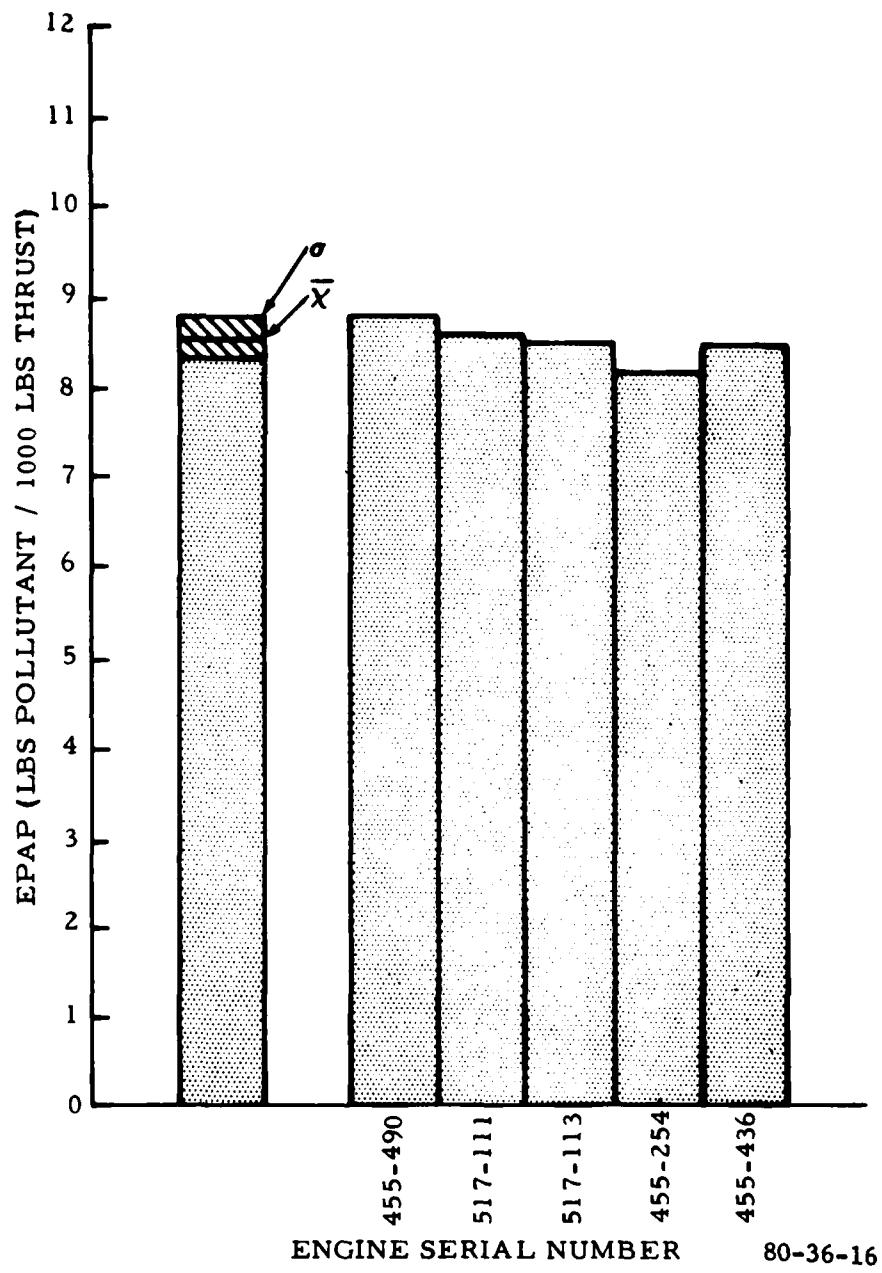


FIGURE 16. OXIDES OF NITROGEN EMISSION LEVELS

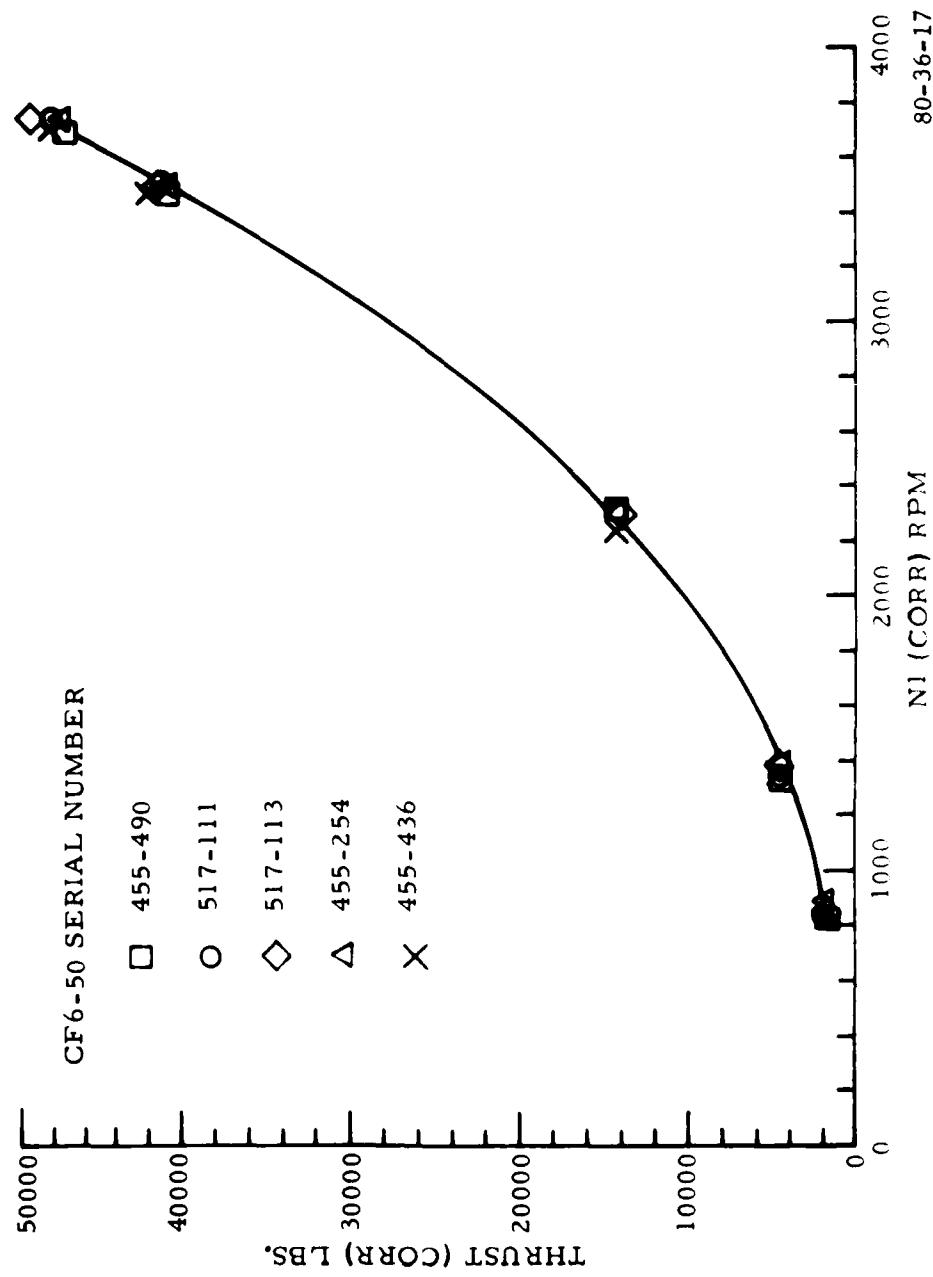


FIGURE 17. FAN SPEED VERSUS THRUST

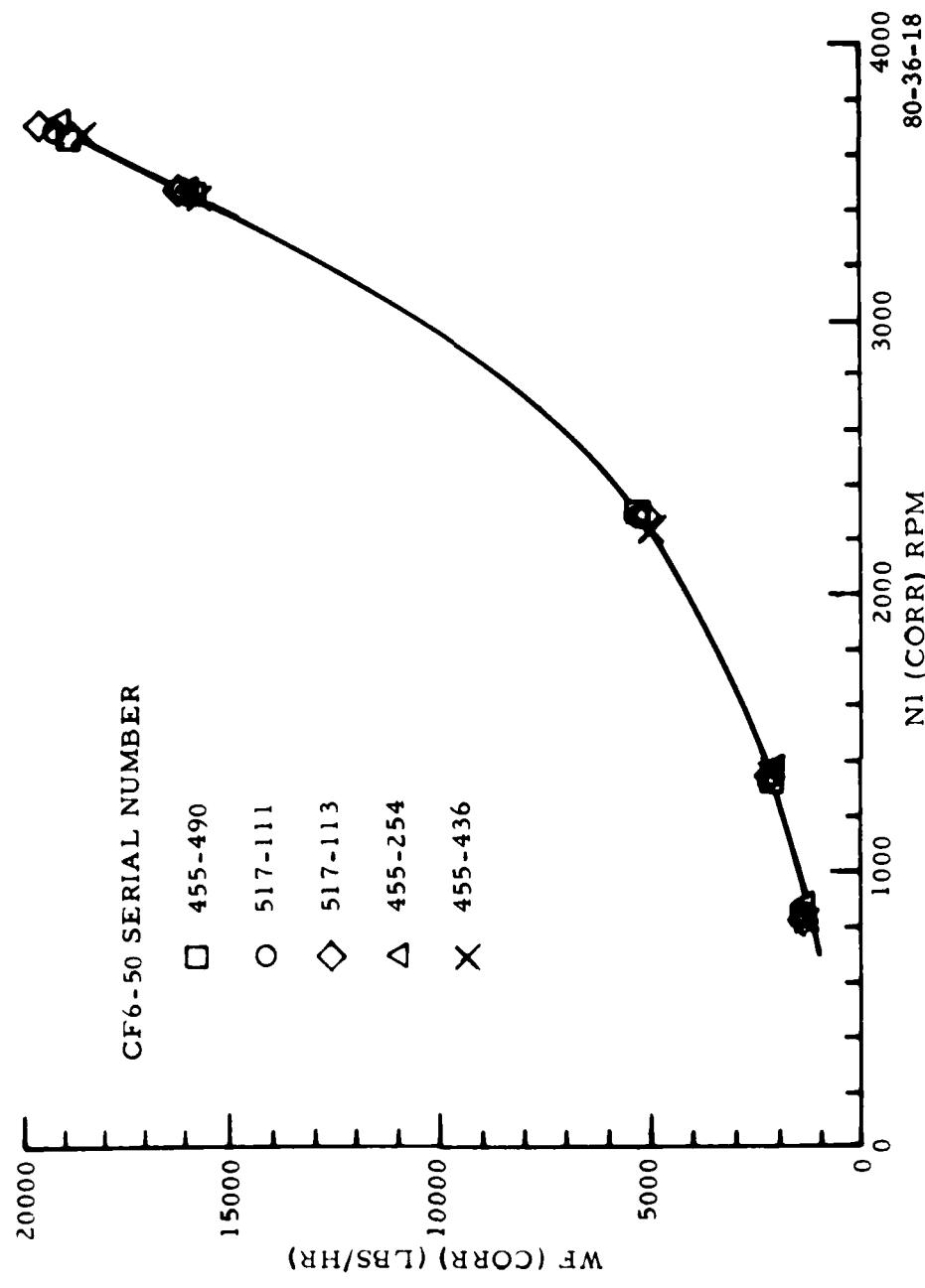


FIGURE 18. FAN SPEED VERSUS FUEL FLOW

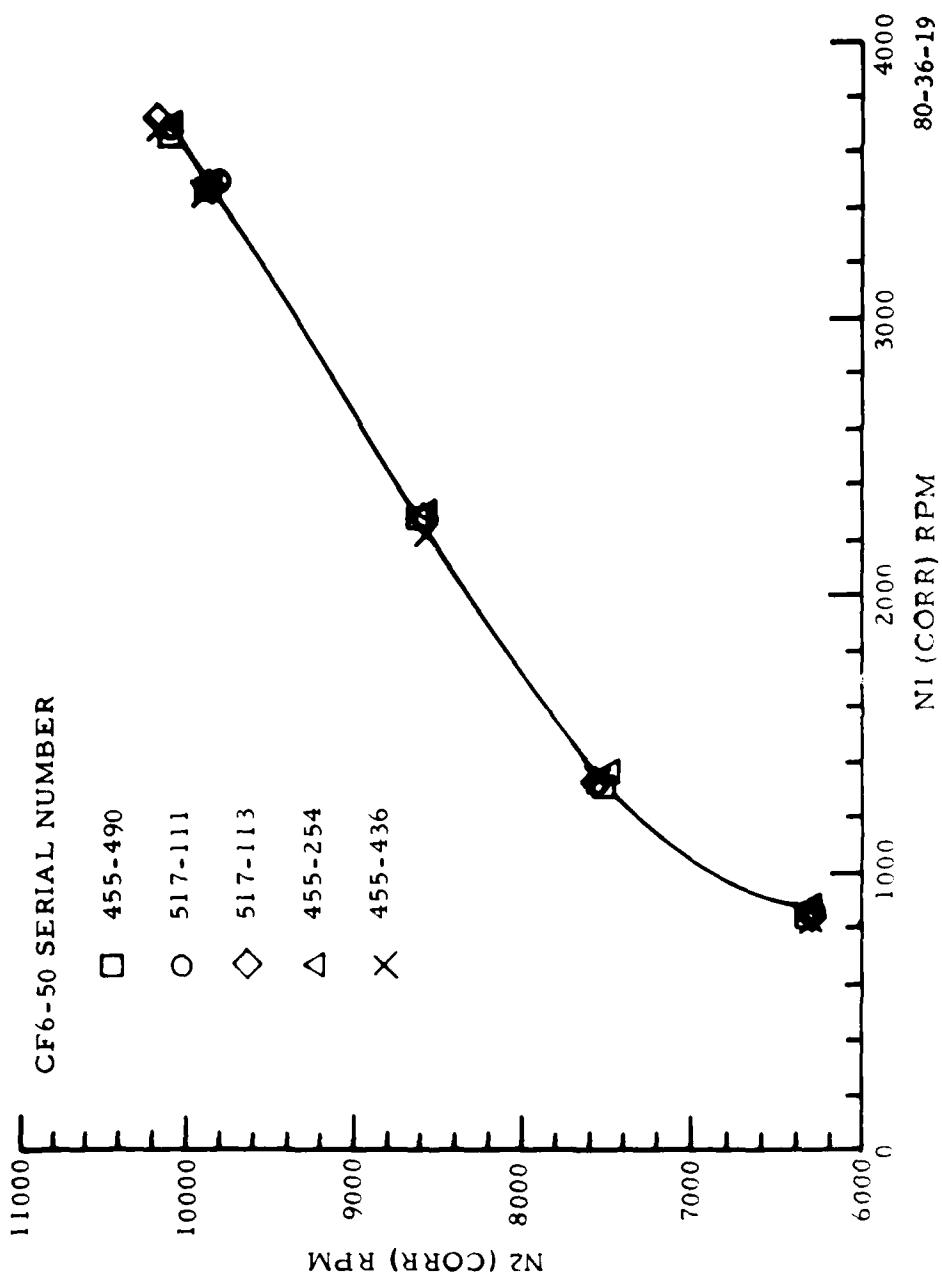


FIGURE 19. FAN SPEED VERSUS CORE SPEED

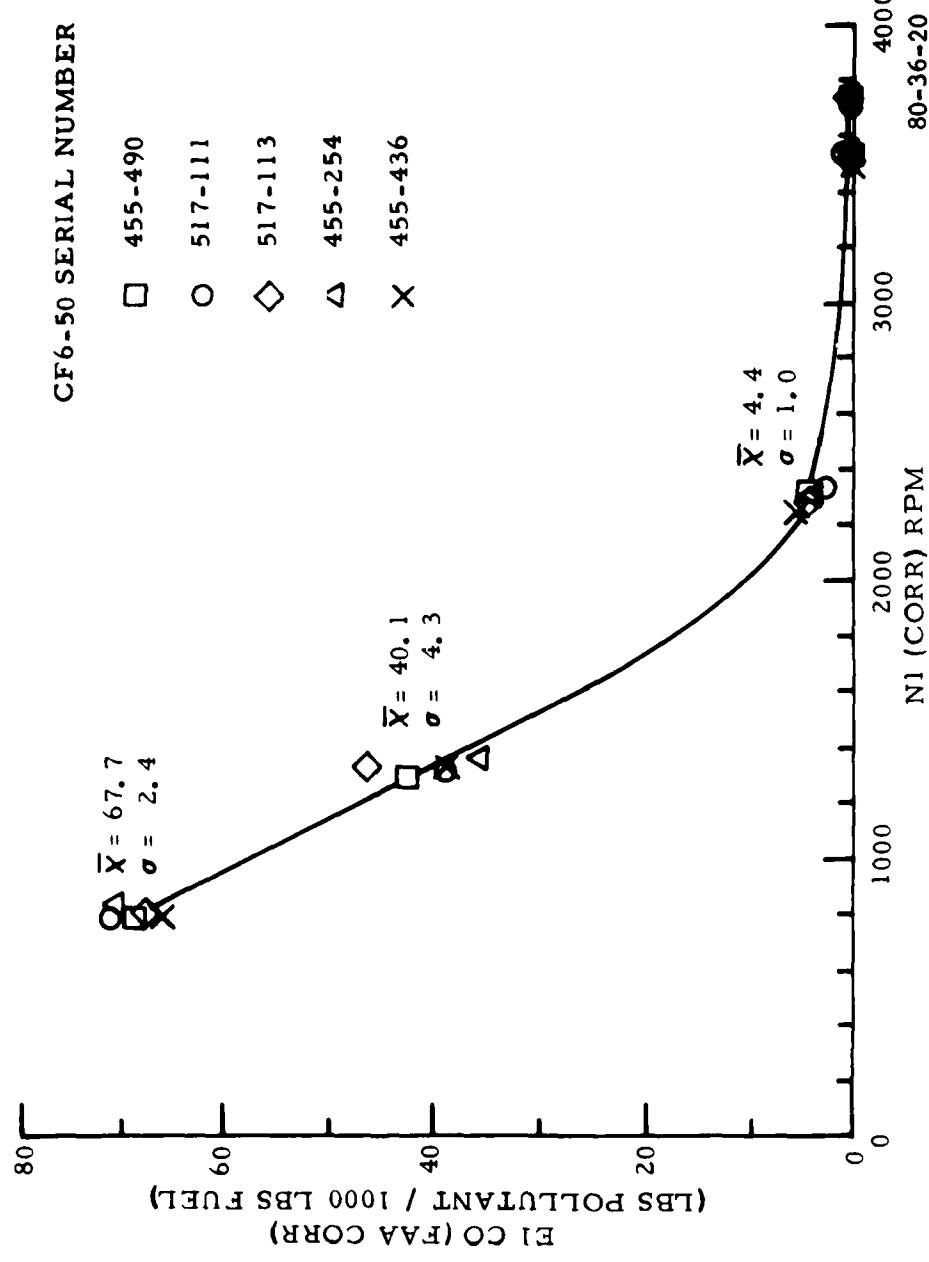


FIGURE 20. FAN SPEED VERSUS EI CO

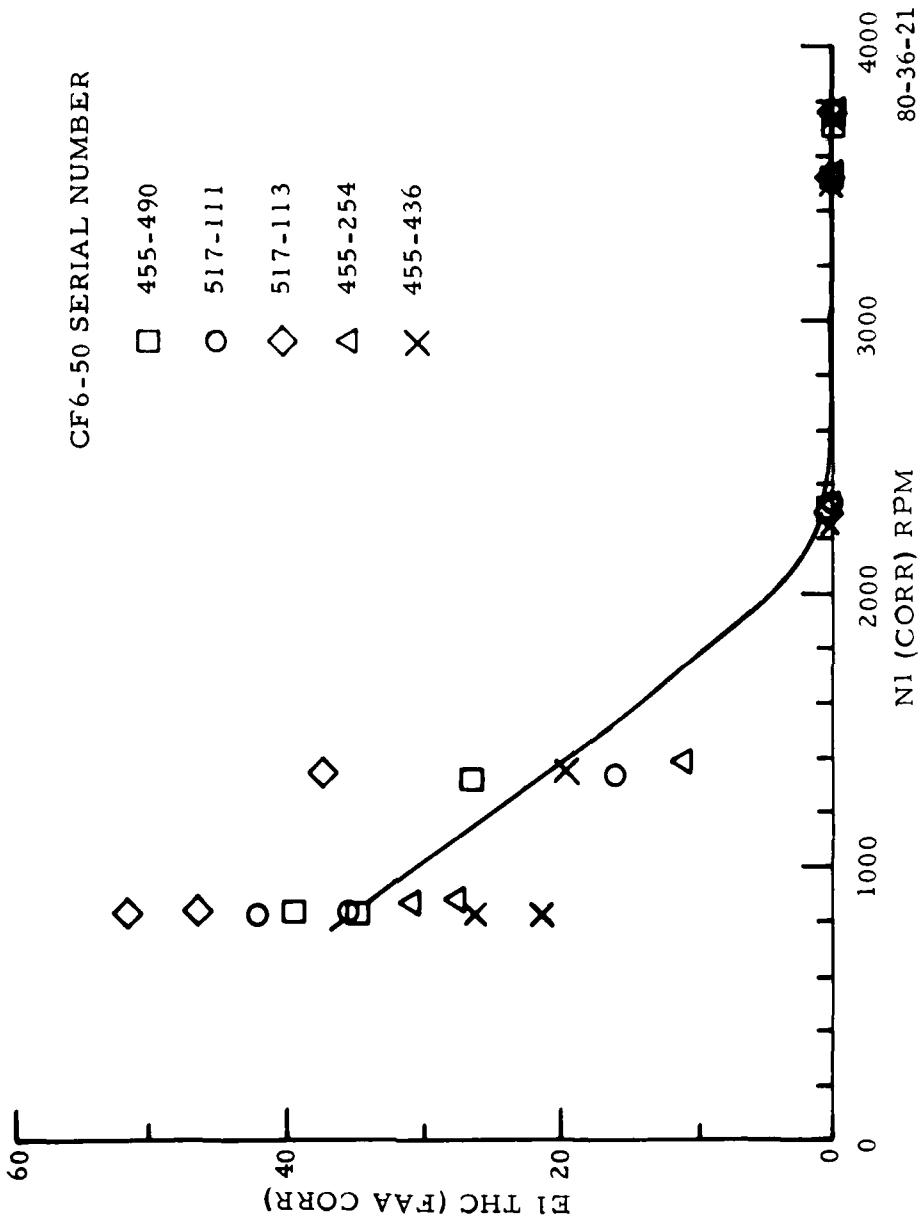


FIGURE 21. FAN SPEED VERSUS EI THC

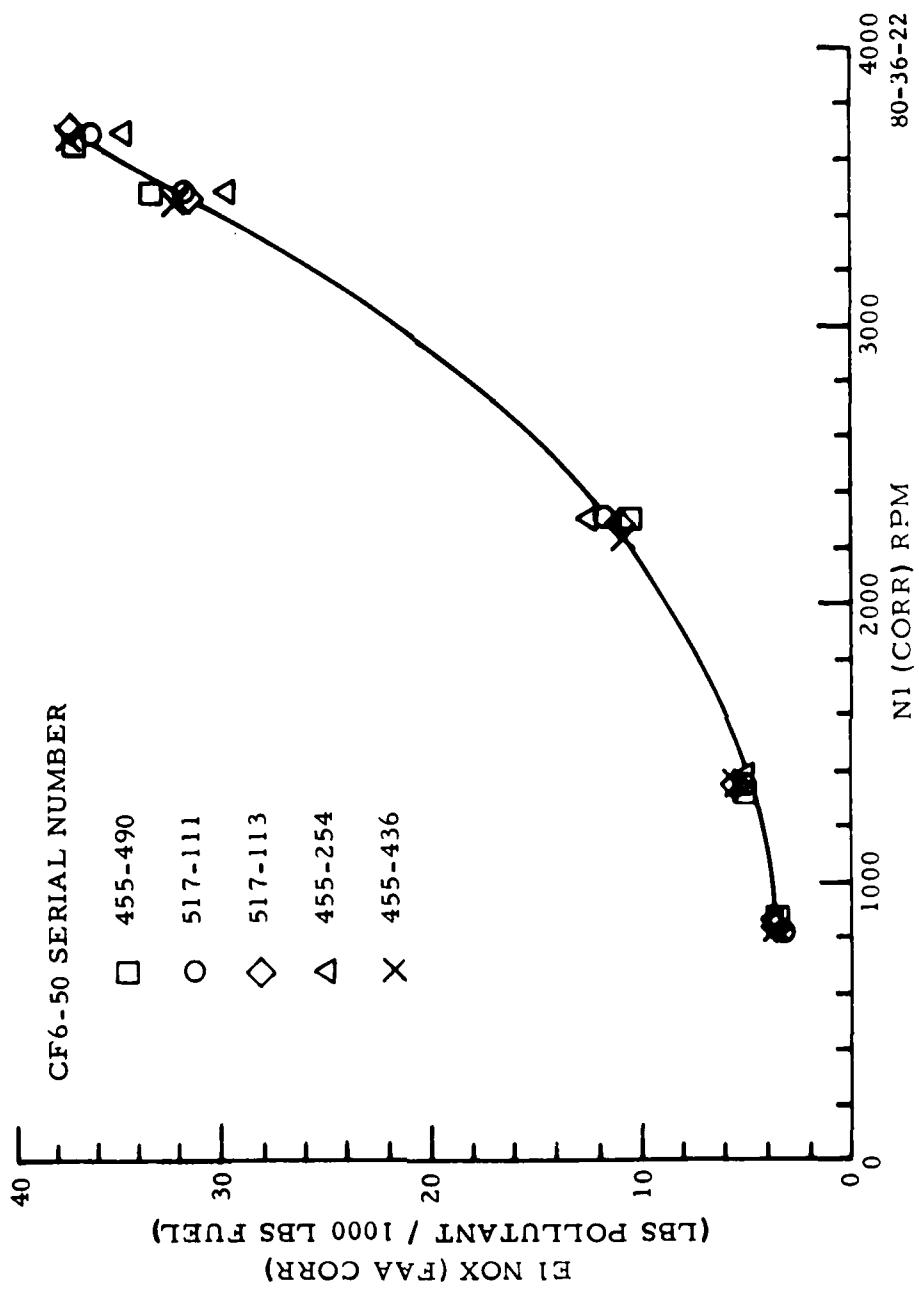


FIGURE 22. FAN SPEED VERSUS EI NO_x

APPENDIX A

AIRCRAFT ENGINE EMISSIONS MEASUREMENT SYSTEM CALIBRATION PROCEDURE

INTRODUCTION.

The information and procedures described in this section are discussed in detail in reference 8.

The purpose of this procedure is to describe in detail the proper calibration techniques of carbon monoxide (CO), carbon dioxide (CO₂), total hydrocarbons (THC) oxides of nitrogen, (NO/NO_x), and oxygen (O₂) analysis.

1. Gases.

The calibration gases should consist of the following:

a. Ranges:

10 ppm to 20 percent carbon monoxide in nitrogen

1 to 20 percent carbon dioxide in nitrogen

5 to 2,500 ppm propane in air

1,000 to 30,000 ppm propane in nitrogen (only used for piston work)

10 to 2,500 ppm nitric oxide in nitrogen

0.01 to 20 percent oxygen in nitrogen

b. Tolerances:

All gases shall have a +0/-5 percent blend tolerance and analysis accuracy of ± 1 percent of true value for concentrations greater than 100 ppm and ± 2 percent of true value for concentrations less than 100 ppm.

c. Selection:

(1) Select a zero gas for each analyzer. This gas should produce a zero percent full-scale reading on the analyzer. Nitrogen should be used for CO, CO₂, and THC analyzers; air should be used for NO/NO_x analyzer.

(2) Select span gases for each analyzer. The concentration of these gases will depend on which range is being calibrated. (See tables A-1 through A-5.) Enough gases should be chosen to properly define a calibration curve for the indicated analyzer and range. This will also depend on the linearity of the instrument.

(a) One span gas should produce a 100 percent full-scale deflection (high span). Two of the span gases should produce approximately 60 and 30 percent full-scale deflection (mid and low spans, respectively). These three gases (high, mid, and low spans) along with the zero gases are minimum requirements for routine calibrations.

2. Emission Instruments (reference ARP number 1534, section 3.1)

3. Carbon Monoxide and Carbon Dioxide Analyzer Calibration

a. Reference ARP number 1534, section 3.1.1(a):

Any lines, valves, or boxes whose heating is essential for testing should be up to temperature.

b. Calibration Curve:

(1) Set the analyzer on the most sensitive range and select the zero gas to each analyzer. Set the flows and let the instrument stabilize (about 1 minute should be sufficient). If the instrument is not indicating zero percent fullscale, set the zero pot where the analyzer reads approximately zero (a

digital voltmeter (VM) is advisable for a more accurate reading).

(2) Change the range and select the high-span gas to each analyzer. Set the flows and let the instruments stabilize. If the instrument does not indicate 100 percent full-scale, adjust the gain pot for 100 percent (approximately) full-scale reading.

(3) Repeat procedures (1) and (2) until both the zero and high-span readings are reproducible to within +0.5 percent full-scale.

(4) Set the proper range and select the mid-span gases to each analyzer. Set the flows and let the instruments stabilize. After stabilization, record the gas concentration along with the percent full-scale response.

NOTE: Do not adjust the zero or gain pot settings when analyzing midrange gases. However, these settings should be checked against the zero and high-span gas periodically during midspan calibration (this is done for the purpose of checking analyzer performance).

(5) After all the gases have been analyzed, a final zero and high-span check is advisable to insure an accurate calibration.

NOTE: The pots should not have to be adjusted at this time. If the gases are not reproducible to within

+0.5 percent, repeat steps (1) and (2) of this procedure.

(6) Repeat steps 1 through 5 at least two more times or until the calibrator is satisfied with the results.

(7) Tabulate the gas concentrations along with average percent full-scale responses.

(8) Perform a third degree polynomial regression on the data.

(9) Plot the results from (8) and record the coefficients. This information will indicate the accuracy of the analyzers and the gases. If the information indicates a malfunction in the analyzer, consult the manual. If a gas does not meet tolerances, check the bottle or consult the manufacturer (see gas tolerances 1b).

(10) If the results from (9) are not reproducible to within +0.5 percent, an analyzer or gas problem is indicated; repeat the entire procedure and troubleshoot system.

4. Linear Analyzer Calibrations.

a. Hydrocarbon Analyzer (reference ARP number 1534, section 3.1.3)

b. Oxides of Nitrogen Analyzer (reference ARP number 1534, section 3.1.4)

c. Oxygen Analyzer (reference ARP number 1534, section 3.1.2)

TABLE A-1. CARBON MONOXIDE GASES*

A. Analyzer Serial Number 0100362

<u>Number</u>	<u>Range 1 (0-2,500 ppm)</u>	<u>Range 2 (0-1,000 ppm)</u>	<u>Range 3 (0-100 ppm)</u>
1	Zero gas	Zero gas	Zero gas
2	19	19	19
3	48	99.1	24
4	99.1	142	48
5	142	403	99.1
6	254	980	
7	403		
8	509		
9	980		
10	1,930		
11	2,450		

B. Analyzer Serial Number 0100530

<u>Number</u>	<u>Range 1 (0-2,500 ppm)</u>	<u>Range 2 (0-1,000 ppm)</u>	<u>Range 3 (0-100 ppm)</u>
1	Zero gas	Zero gas	Zero gas
2	24	24	24
3	73	73	48
4	98.7	98.7	73
5	254	254	98.7
6	368	368	
7	509	509	
8	967	967	
9	1,360		
10	1,930		
11	2,450		

C. Analyzer Serial Number 0100543

<u>Number</u>	<u>Range 1 (0-2,500 ppm)</u>	<u>Range 2 (0-1,000 ppm)</u>	<u>Range 3 (0-100 ppm)</u>
1	Zero gas	Zero gas	Zero gas
2	98.7	24	24
3	125	73	48
4	254	98.7	73
5	368	125	94
6	509	254	
7	1,000	368	
8	1,360	509	
9	1,930	1,000	
10	2,450		

* See Section 1b for Blend Tolerances.

NOTE: Five gases and a zero are sufficient for ranges 2 and 3.

TABLE A-2. CARBON DIOXIDE GASES

A. Analyzer Serial Number 0100030

<u>Number</u>	<u>Range 1 (0-5%)</u>	<u>Range 2 (0-3%)</u>	<u>Range 3 (0-2%)</u>
1	Zero gas	Zero gas	Zero gas
2	0.50	0.50	0.50
3	1.00	1.00	1.00
4	1.49	1.49	1.49
5	2.00	2.00	2.00
6	2.96	2.96	
7	4.91	2.99	
8	5.00		

B. Analyzer Serial Number 0101150

<u>Number</u>	<u>Range 1 (0-5%)</u>	<u>Range 2 (0-3%)</u>	<u>Range 3 (0-2%)</u>
1	Zero gas	Zero gas	Zero gas
2	0.50	0.50	0.50
3	1.00	1.00	1.00
4	1.49	1.49	1.49
5	1.96	1.96	1.96
6	2.90	2.90	
7	4.91		

C. Analyzer Serial Number 0101157

<u>Number</u>	<u>Range 1 (0-5%)</u>	<u>Range 2 (0-3%)</u>	<u>Range 3 (0-2%)</u>
1	Zero gas	Zero gas	Zero gas
2	0.25	0.25	0.25
3	0.49	0.49	0.49
4	1.49	1.49	1.49
5	2.03	2.03	2.03
6	2.95	2.95	
7	4.03		
8	5.27		

TABLE A-3. HYDROCARBON GASES (PROPANE)

A. Analyzer Serial Number 0100078

	(ppm)
1	Zero gas
2	24.8
3	49.7
4	97.9
5	101
6	494
7	981

B. Analyzer Serial Number 0100257

	(ppm)
1	Zero gas
2	38
3	98.1
4	501
5	984

C. Analyzer Serial Number 0100256

	(ppm)
1	Zero gas
2	26
3	38
4	51
5	74
6	100
7	248
8	1,000

TABLE A-4. OXIDES OF NITROGEN GASES

A. Analyzer Serial Number 0100000

	(ppm)
1	Zero gas
2	50.9
3	93.5
4	403

B. Analyzer Serial Number 0100007

	(ppm)
1	Zero gas
2	100
3	247
4	975

C. Analyzer Serial Number 0100010

	(ppm)
1	Zero gas
2	88
3	118
4	247
5	490

TABLE A-5. OXYGEN GASES

A. Analyzer Serial Number 1,284-704

	(%)
1	0.10
2	0.50
3	10.00
4	Blended air

B. Analyzer Serial Number 1,145-608

	(%)
1	0.10
2	5.00
3	10.00
4	Blended air

C. Analyzer Serial Number 1,277-704

	(%)
1	0.10
2	5.00
3	10.00
4	Blended air

APPENDIX B

MOBILE EMISSION RESEARCH FACILITY (MERF) START UP, CALIBRATION, AND OPERATION CHECK LIST

1. Connect sample line
2. Change FID filter
3. Turn on heater control circuit breaker
4. Turn on FID heat controller
5. Turn on data acquisition system power (calculator, printer, cassette, expander, scanner, DVM)
6. Turn on all gas bottles
7. Turn on cylinder room fan
8. Log bottle pressure (at end of test)

Note: Change gas bottles at 200 pounds per square inch (psi), enter change on "MERF calibration data" tape.

9. Verify heater controllers set properly

Hi temp lines - 300° F

Hi temp box - 300° F

Sample line - 320° F

Lo temp lines - 160° F

Lo temp box - 150° F

10. Set sensotec pressure indicator balance and span (set pressure selector to CAL)

11. Set pressure selector to FID

12. Switch panel:

- A. Turn on dryer
- B. Select wet or dry
- C. Open drain for 3 seconds
- D. Turn on ozone
- E. Select probe purge/room air

13. Data acquisition system start-up

- A. Insert "MERF Operations Programs" into primary tape drive
- B. Insert MERF Calibration Data" into number 3 tape drive
- C. Key in "Load 2 Execute", then "Run Execute"

- D. Follow instructions to "Input Rdg, I.D."

14. Switch panel:

- A. Turn on fuel and air to FID
15. 951H_x Analyzer: (NO-NO_x)

- A. Turn on ozonizer

- B. Select span

16. 402 analyzer: (FID)

- A. Select "override"
- B. Set fuel and air pressure to "start"

- C. Depress ignitor; hold until flame-out indicator goes off

- D. Select "normal"

- E. Do not increase air pressure at this time

17. 864 Analyzer: (CO₂)

- A. Select "tune"
 - B. Verify correct oscillator tuning of 40
18. 865 analyzer: (CO)
- A. Select "tune"
 - B. Verify correct analyzer tuning of 40
19. Turn on chopper motor switch
20. 402 analyzer: (FID)
- Increase fuel and air pressure to normal settings
21. OM-11 analyzer: (O_2)
- Depress "operate"
22. Perform leak check
- (Block sample inlet, turn on pumps, should reach approximately 22-inch Hg vacuum)
23. Shut off pumps
24. Analyzer standardization:
- A. Determine next calibration number by checking previous day's data in log book or "TLIST" zero/span check tape
 - B. Key in calibration identification number
 - C. Select zero gas to all analyzers
 - D. Select most sensitive ranges used
 - E. Adjust flows and pressures
 - F. Use calculator keys to set zero
 - G. Select least sensitive ranges
 - H. Select HI span to all analyzers
 - I. Adjust flows and pressures
 - J. Use calculator keys to set span
 - K. Select zero gas
 - L. Select most sensitive ranges used
 - M. Recheck zero settings
 - N. Record zero data (continue program)
 - O. Select least sensitive range
 - P. Record data
 - Q. Select HI span
 - R. Stabilize
 - S. Record data
 - T. Select MID span
 - U. Stabilize
 - V. Record data
 - W. Select MID range
 - X. Stabilize
 - Y. Record Data
 - Z. Select LO span
 - AA. Stabilize
 - BB. Record data
 - CC. Select LO range
 - DD. Stabilize
 - EE. Record data
 - FF. Select probe purge/room air
 - GG. Adjust OM-11 flow to "5"

HH. Adjust OM-11 for proper O₂ reading

II. Stabilize

JJ. Record data

25. Prior to engine start:

A. Pumps off

B. Select probe purge/room air

C. Turn on nitrogen gas purge and adjust to 5 psi

26. After engine start:

A. Turn off purge

B. Pump on

C. Select proper range for engine power (response greater than 40 percent full scale on all analyzers, if possible)

D. Select sample

E. Verify correct flows and pressures

F. Verify proper system operation

G. Check temperatures

H. Select room air

27. Sampling:

A. Select sample one minute before end of engine stabilization period

B. Select proper ranges for engine power

C. Key in proper "reading I.D."

D. Verify correct analyzer flow

E. Verify correct 402 analyzer auxilliary range setting

F. Verify correct 951H_x analyzer mode

G. Verify data acquisition system is flashing "STAND BY"

H. At test engineer's signal, select sample on data acquisition system for one minute

I. Switch off data acquisition

J. Allow time for data to store on tapes

K. Select room air

28. Analyzer restandardization:

(at least once per test sequence or every 30 minutes, whichever is sooner, all analyzers must be restandardized)

A. Key in calibration I.D. number

B. Select zero gas to all analyzers

C. Select most sensitive range used

D. Adjust flows and pressures

E. Record data

F. If any data is greater than 2 percent off of target, use keys to reset zero

G. Key in calibration I.D. number

H. Record adjusted data.

I. Select least sensitive range

J. Select HI span gas

K. Adjust flows and pressures

L. Record data

M. If any data are greater than 2 percent off of target, use keys to reset span

N. Key in calibration I.D. number

O. Record adjusted data

P. Set up for sampling (see
step 27)

APPENDIX C

FUEL ANALYSIS FIA ANALYSIS

<u>SAMPLE</u>	<u>NITROGEN (mg/l)</u>	<u>HYDROGEN (wt %)</u>	<u>AROMATICS (vol %)</u>	<u>OLEFINS (vol %)</u>	<u>H/C RATIO (wt/wt)</u>	<u>(mol/mol)</u>
Fuel sample 9/30/79 ESN 517-437	0.5	13.8	18.0	0.0	0.160	1.92
Fuel sample 7/19/79 ESN 517-490	1.3	14.0	17.5	0.0	--	--
Fuel Sample 8/4/79 ESN 517-111	0.8	13.9	16.5	0.0	--	--
Fuel Sample 8/9/79 ESN 517-113	0.5	13.8	18.0	0.0	--	--
Fuel Sample 8/14/79 ESN 455-254	0.9	13.8	19.5	0.0	--	--

-- Not Analyzed

APPENDIX D
UNCORRECTED EMISSION AND ENGINE DATA

TEST DATE 7/19/79

ESN 455-490

<u>MODE POWER</u>	<u>1 IDLE OUT</u>	<u>2 IDLE +</u>	<u>3 T.O.</u>	<u>4 85%</u>	<u>5 30%</u>	<u>6 IDLE IN</u>
CO (dry) ppm	704.37	420.72	11.60	10.56	44.17	685.45
CO ₂ (dry) %	1.99	1.96	4.08	3.76	2.40	1.91
THC (wet) ppm C	519.84	363.84	6.43	5.60	6.05	536.32
NO _x (WET) ppm	19.20	26.81	430.29	352.11	72.63	18.53
O ₂ (DRY) %	17.75	17.79	14.64	14.99	16.99	17.63
Ambient Pressure P _{amb} (in/Hg)	28.091	28.901	28.901	28.901	28.901	28.901
HUMIDITY (grains)	82	82	82	82	82	82
N ₁ (rpm)	866.1	1364.4	3833.4	3641.1	2400.8	873.1
N ₂ (rpm)	6506.2	7726.1	10380.3	10136.9	8906.1	6551.6
Fuel Flow W _f (lbs/hr)	1349.2	2155.1	18502.7	15810.6	5068.2	1306.6
Air Flow W _a (lbs/sec)	37.485	63.391	261.654	238.439	124.173	38.013
Turbine Discharge Pressure TDP (in/Hg)	33.374	41.434	177.181	157.666	71.993	33.394
Exhaust Gas Temperature EGT (°R)	1247.2	1245.1	2055.2	1960.1	1460.6	1254.7
Compressor Inlet Pressure CIP (in/Hg)	28.891	28.893	28.699	28.685	28.793	28.879
Compressor Inlet Temperature CIT (°F)	88.931	90.750	91.828	91.491	92.513	93.123
Compressor Discharge Temperature CDT (°R)	777.51	910.79	1440.04	1397.40	1115.01	779.84
F _n Thrust (lbf)	1705.2	4167.68	45288.1	39516.4	13535.0	1706.7
FUEL/AIR Ratio (from emission data)	0.010134	0.009779	0.019372	0.017881	0.011509	0.009753
FUEL/AIR Ratio (from engine data)	0.009998	0.009444	0.019643	0.018419	0.011338	0.009548

TEST DATE 8/04/79

ESN 517-111

<u>MODE POWER</u>	<u>1 IDLE OUT</u>	<u>2 IDLE +</u>	<u>3 T.O.</u>	<u>4 85%</u>	<u>5 30%</u>	<u>6 IDLE IN</u>
CO (dry) ppm	703.89	389.02	11.96	12.60	31.68	705.18
CO ₂ (dry) %	2.04	2.01	4.23	3.88	2.49	1.91
THC (wet) ppm C	541.27	232.01	0.28	0.00	0.14	591.39
NO _x (WET) ppm	19.91	28.11	428.59	339.27	83.68	20.57
O ₂ (DRY) %	17.54	17.56	14.51	14.91	16.97	17.57
Ambient Pressure P _{amb} (in/Hg)	28.956	28.946	28.946	28.946	28.946	28.946
HUMIDITY (grains)	76	76	76	76	76	76
N ₁ (rpm)	867.1	1380.5	3844.1	3630.4	2389.4	873.1
N ₂ (rpm)	6458.4	7714.4	10313.9	10053.4	8815.3	6490.5
Fuel Flow W _f (lbs/hr)	1336.5	2159.71	18715.8	15712.4	5244.7	1322.7
Air Flow W _a (lbs/sec)	31.217	38.816	261.000	236.953	121.305	31.394
Turbine Discharge Pressure TDP (in/Hg)	N/A	N/A	N/A	N/A	N/A	N/A
Exhaust Gas Temperature EGT (°R)	1239.6	1241.97	2090.0	1981.3	1461.0	1237.1
Compressor Inlet Pressure CIP (in/Hg)	28.936	28.919	28.695	28.718	28.866	28.936
Compressor Inlet Temperature CIT (°F)	85.009	86.566	85.948	85.004	86.298	88.605
Compressor Discharge Temperature CDT (°R)	778.99	915.89	1448.22	1400.82	1119.81	780.01
F _n Thrust (lbs _f)	1745.0	4391.9	46099.9	39499.3	13776.8	1515.5
FUEL/AIR Ratio (from emission data)	0.010382	0.009937	0.020066	0.018438	0.011925	0.009790
FUEL/AIR Ratio (from engine data)	0.011893	0.015455	0.019919	0.018419	0.012010	0.011703

TEST DATE 8/09/79

ESN 517-113

<u>MODE POWER</u>	<u>1 IDLE OUT</u>	<u>2 IDLE +</u>	<u>3 T.O</u>	<u>4 85%</u>	<u>5 30%</u>	<u>6 IDLE IN</u>
CO (dry) ppm	700.60	455.98	10.96	10.86	40.4	686.76
CO ₂ (dry) %	1.98	1.92	4.25	3.84	2.33	1.90
THC (wet) ppm C	714.19	538.82	4.06	3.47	4.74	744.16
NO _x (WET) ppm	20.26	29.98	441.06	335.50	74.80	20.22
O ₂ (DRY) %	17.60	17.65	14.16	14.62	16.75	17.29
Ambient Pressure Pamb (in/Hg)	20.020	29.019	29.019	29.019	29.019	29.019
HUMIDITY (grains)	70	70	70	70	70	70
N ₁ (rpm)	877.0	1390.0	3855.3	3606.0	2365.3	874.8
N ₂ (rpm)	6463.0	7718.2	10394.2	10086.5	8843.8	6454.8
Fuel Flow W _f (lbs/hr)	1390.0	2191.9	19107.1	15525.4	5027.0	1311.9
Air Flow W _a (lbs/sec)	31.975	66.237	264.323	238.686	121.640	31.853
Turbine Discharge Pressure TDP (in/Hg)	N/A	42.310	180.039	156.585	60.983	29.015
Exhaust Gas Temperature EGT (°R)	N/A	1224.42	2067.0	1943.6	1417.3	1200.3
Compressor Inlet Pressure CIP (in/Hg)	29.011	28.997	28.754	28.801	28.944	29.011
Compressor Inlet Temperature CIT (°F)	81.00	82.963	82.488	83.668	85.280	84.782
Compressor Discharge Temperature CDT (°R)	N/A	918.87	1467.18	1398.18	1115.76	782.4
F _n Thrust (lbf)	1706.5	4469.9	47473.1	39843.9	13428.6	1761.1
FUEL/AIR Ratio (from emission data)	0.010180	0.009692	0.020161	0.018253	0.011175	0.009808
FUEL/AIR Ratio (from engine data)	0.012075	0.009192	0.020080	0.018068	0.011480	0.011441

TEST DATE 8/14/79

ESN 455-254

<u>MODE POWER</u>	<u>1 IDLE OUT</u>	<u>2 IDLE +</u>	<u>3 T.O.</u>	<u>4 85%</u>	<u>5 30%</u>	<u>6 IDLE IN</u>
CO (dry) ppm	757.29	367.07	12.73	11.87	47.07	786.08
CO ₂ (dry) %	2.22	2.05	4.40	4.05	2.49	2.14
THC (wet) ppm C	469.62	169.54	1.28	0.55	2.04	507.00
NO _x (WET) ppm	21.75	27.88	415.38	326.03	88.54	20.44
O ₂ (DRY) %	17.23	17.46	14.18	14.52	16.59	17.04
Ambient Pressure Pamb (in/Hg)	29.011	20.011	29.011	29.011	29.011	29.011
HUMIDITY (grains)	70	70	70	70	70	70
N ₁ (rpm)	908.6	1416.6	3826.3	3595.2	2373.4	898.9
N ₂ (rpm)	6430.8	7611.0	10257.1	9965.9	8735.3	6402.0
Fuel Flow W _f (lbs/hr)	1351.0	2142.1	18501.4	15313.6	5101.3	1324.5
Air Flow W _a (lbs/sec)	40.992	67.955	260.185	237.841	124.539	40.368
Turbine Discharge Pressure TDP (in/Hg)	33.963	42.239	176.116	155.117	71.759	33.653
Exhaust Gas Temperature EGT (°R)	1223.6	1218.75	2063.3	1949.2	1426.8	1217.6
Compressor Inlet Pressure CIP (in/Hg)	28.999	28.980	28.789	28.809	28.930	28.999
Compressor Inlet Temperature CIT (°F)	79.359	80.352	79.278	70.03	81.014	80.875
Compressor Discharge Temperature CDT (°R)	778.15	910.13	1444.03	1390.84	1108.48	774.11
F _n Thrust (lbs _f)	1829.5	4445.9	45613.6	38999.0	13659.6	1766.7
FUEL/AIR Ratio (from emission data)	0.011226	0.010086	0.020856	0.019230	0.011934	0.010879
FUEL/AIR Ratio (from engine data)	0.009155	0.008756	0.019752	0.017885	0.011378	0.009114

TEST DATE 9/30/79

ESN 455-436

<u>MODE</u> <u>POWER</u>	<u>1</u> <u>IDLE OUT</u>	<u>2</u> <u>IDLE +</u>	<u>3</u> <u>T.O.</u>	<u>4</u> <u>85%</u>	<u>5</u> <u>30%</u>	<u>6</u> <u>IDLE IN</u>
CO (dry) ppm	707.07	386.08	9.04	4.49	60.43	694.21
CO ₂ (dry) %	2.10	1.96	4.00	3.75	2.39	2.03
THC (wet) ppm C	403.20	297.42	5.65	4.51	6.13	417.26
NO _x (WET) ppm	20.96	28.48	385.79	315.00	69.73	20.32
O ₂ (DRY) %	17.13	17.14	14.60	14.74	17.03	17.73
Ambient Pressure Pamb (in/Hg)	29.037	29.037	29.037	29.037	29.037	29.037
HUMIDITY (grains)	80	80	80	80	80	80
N ₁ (rpm)	839.9	1377.9	3785.7	3548.3	2281.3	845.1
N ₂ (rpm)	6407.5	7679.8	10302.3	10069.2	8711.3	6429.5
Fuel Flow W _f (lbs/hr)	1286.3	2126.6	17893.4	15251.0	4909.0	1290.6
Air Flow W _a (lbs/sec)	37.300	65.448	270.953	242.727	122.714	37.417
Turbine Discharge Pressure TDP (in/Hg)	33.193	41.569	178.854	157.110	70.063	33.195
Exhaust Gas Temperature ECT (°R)	1254.8	1226.1115	2010.1	1916.1	1402.4	1245.0
Compressor Inlet Pressure CIP (in/Hg)	29.036	29.007	28.781	28.803	28.023	29.036
Compressor Inlet Temperature CIT (°F)	74.426	76.452	76.436	76.153	76.627	77.651
Compressor Discharge Temperature CDT (°R)	778.08	919.47	1462.38	1403.66	1112.65	778.32
F _n Thrust (lbs _f)	1668.8	4454.0	46385.7	40631.4	13816.6	1647.4
FUEL/AIR Ratio (from emission data)	0.010798	0.009730	0.018998	0.017830	0.011469	0.010269
FUEL/AIR Ratio (from engine data)	0.009579	0.009026	0.018344	0.017453	0.011112	0.009581

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